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Investigating traditional fluid instabilities in an HED regime

Tiffany Desjardins

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Acknowledgements

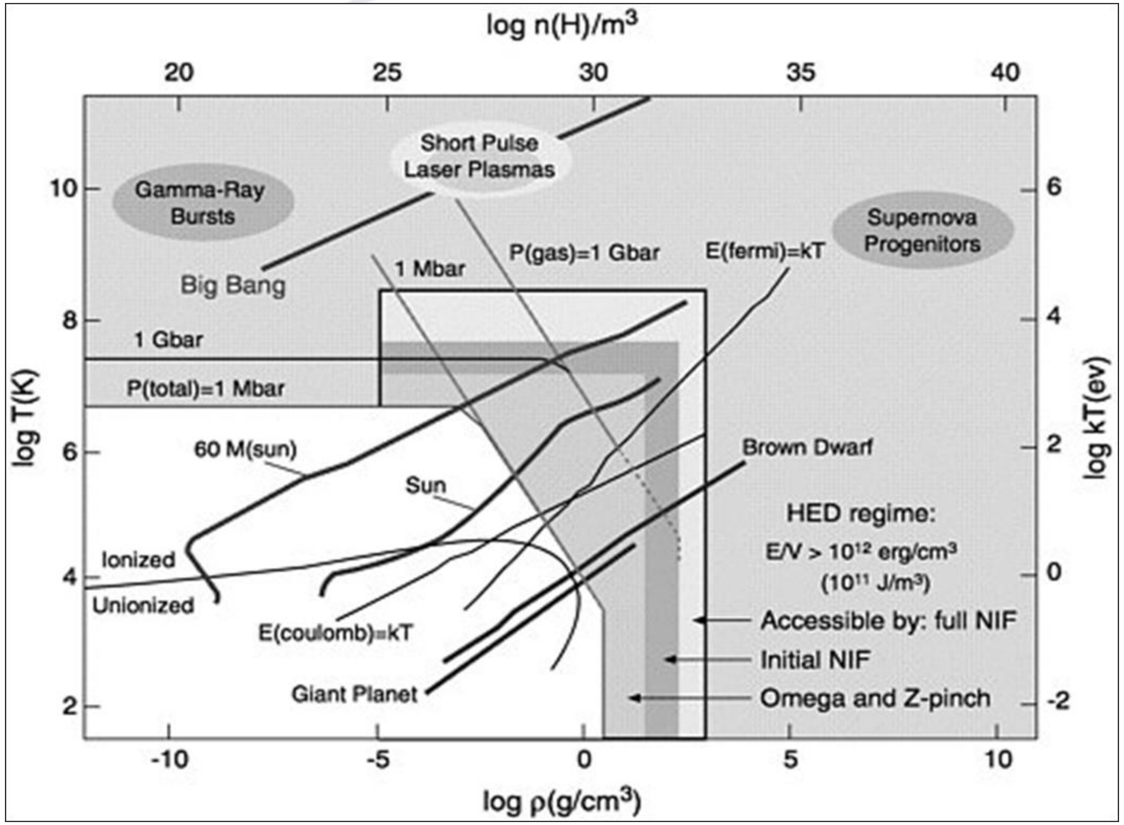
Experimentalist:
- Kirk Flippo
- Elizabeth Merritt
- Sasi Palaniyappan
- Tiffany Desjardins

Designers
- Forrest Doss
- Carlos Di Stefano
- Barbara DeVolder
- Josh Sauppe

Target Fabrication
- Derek Schmidt
- Tom Day

Motivation

High-energy-density systems are defined as systems having pressures above 1 Mbar or energy densities above 100 GJ/m³



R.P. Drake, *High-Energy-Density Physics*

HED systems are characterized by large pressure, which can mean high temperature, high density or both

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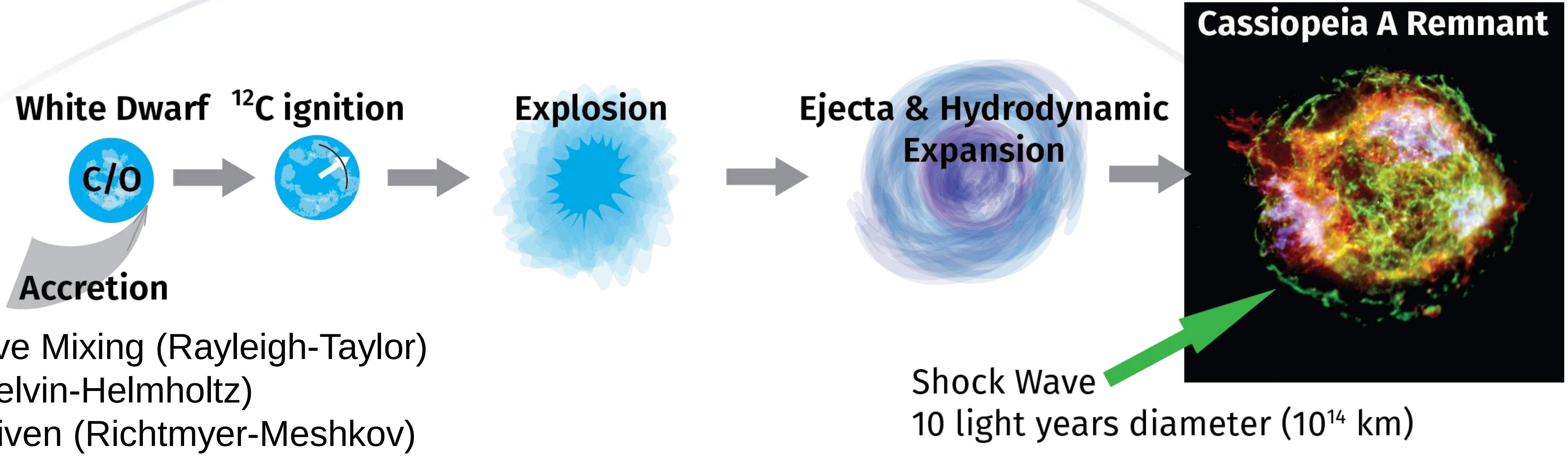
Operated by Los Alamos National Security, LLC for the U.S. Department of Energy's NNSA

Type Ia supernovae are “standard candles” that help determine the age of the universe



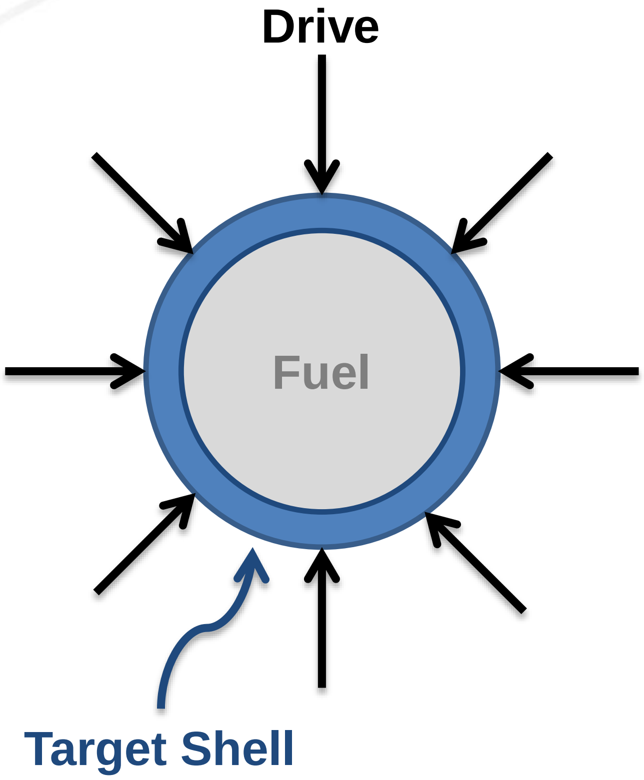
Convective Mixing (Rayleigh-Taylor)
Shear (Kelvin-Helmholtz)
Shock-driven (Richtmyer-Meshkov)

Instabilities are important in:
- Pre-ignition conditions
- Triggering ignition
- Final chemical structure

Image from NASA’s Chandra X-Ray Observatory chandra.harvard.edu

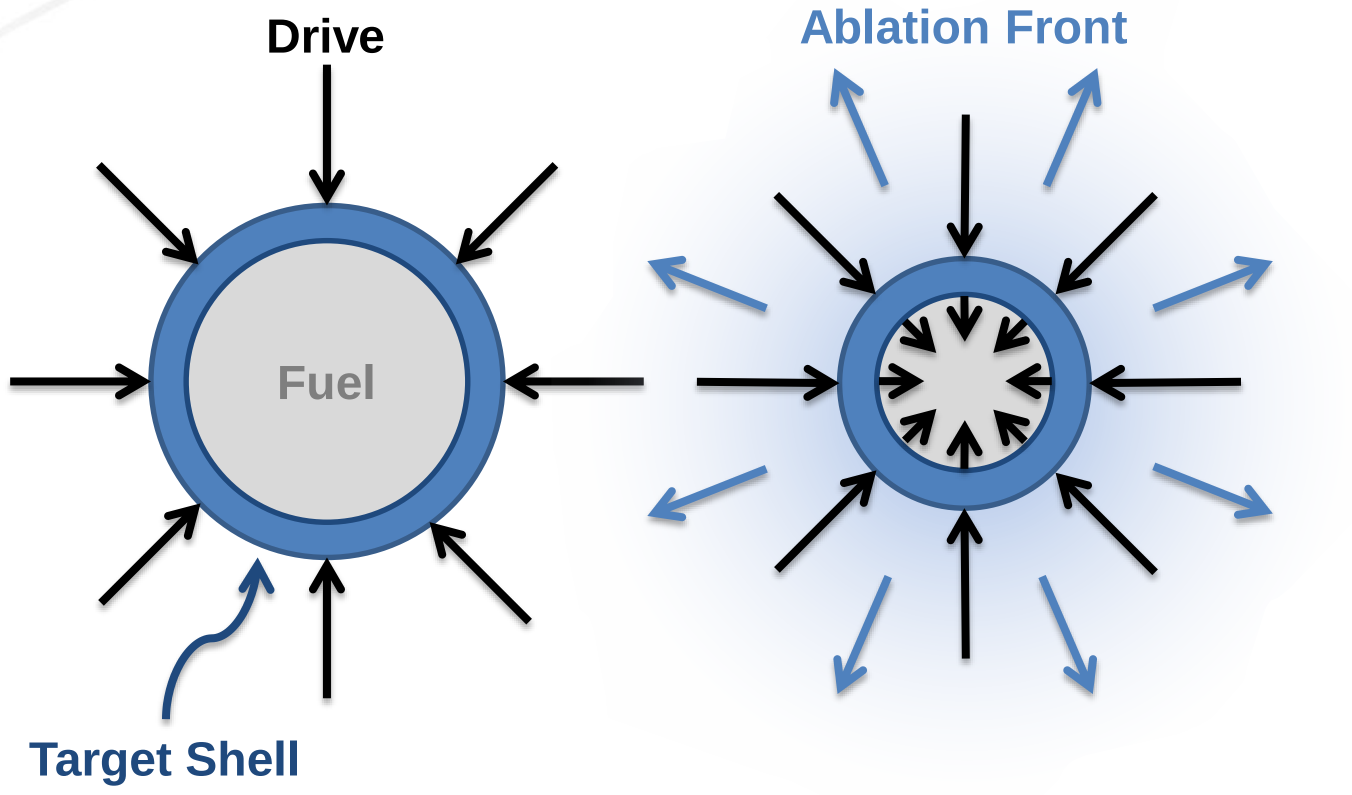
Slide courtesy of Kathy Prestridge

Inertial Confinement Fusion (ICF) seeks to use high power lasers to generate fusion by compressing DT fuel



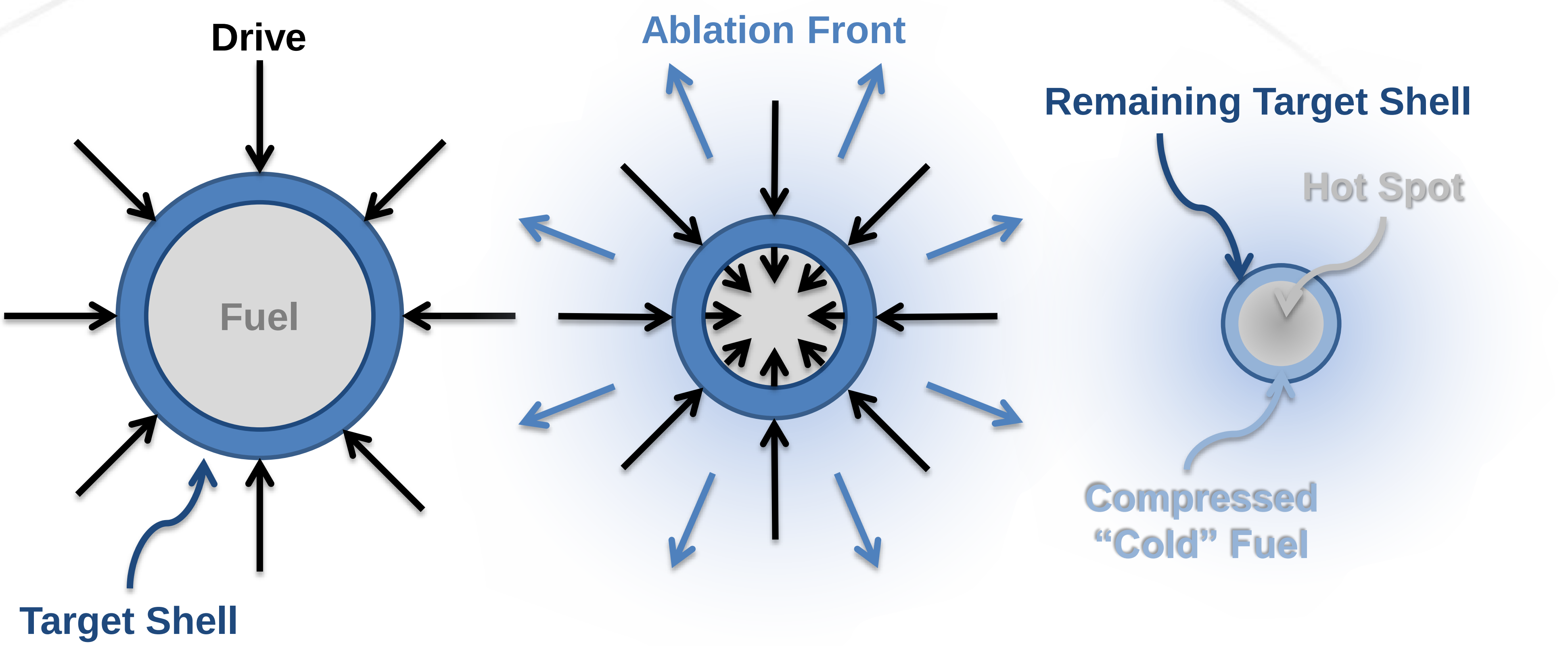
Slide courtesy of Elizabeth Merritt

Inertial Confinement Fusion (ICF) seeks to use high power lasers to generate fusion by compressing DT fuel



Slide courtesy of
Elizabeth Merritt

Inertial Confinement Fusion (ICF) seeks to use high power lasers to generate fusion by compressing DT fuel

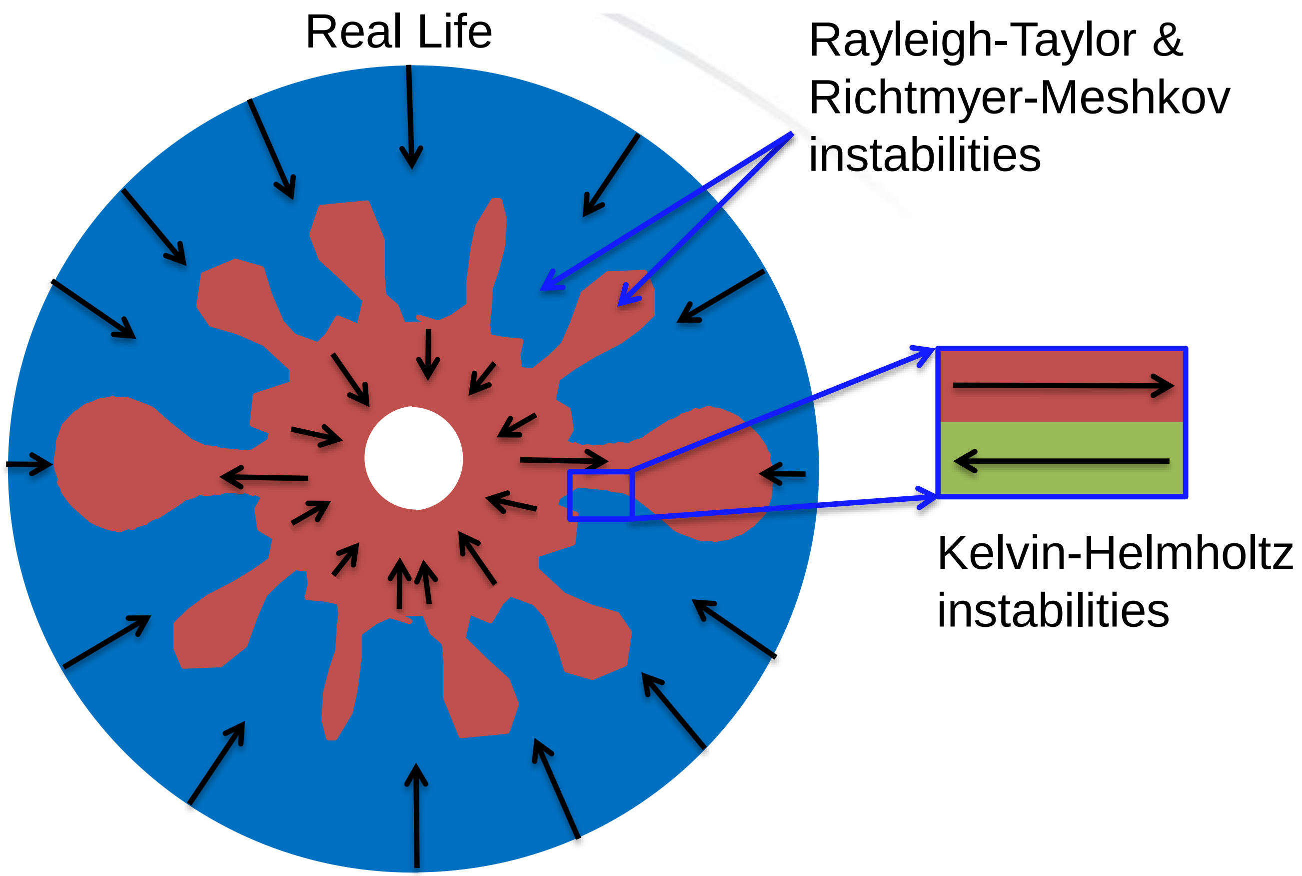


This is ideally how the process should work, but…

Slide courtesy of Elizabeth Merritt

ICF capsules are prone to instabilities at interfaces

- Different target layer densities
  - Rayleigh-Taylor
- Strong Shear flows
  - Kelvin-Helmoltz
- Multiple shocks
  - Richtmyer-Meshkov

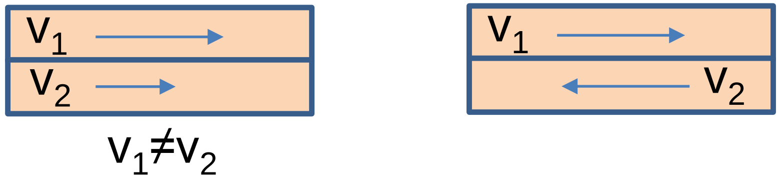


Instabilities can mix ablator material into the fuel and degrade and/or prevent ignition

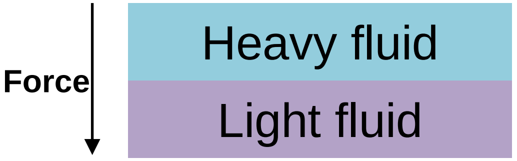
Slide courtesy of Kathy Prestridge and Elizabeth Merritt

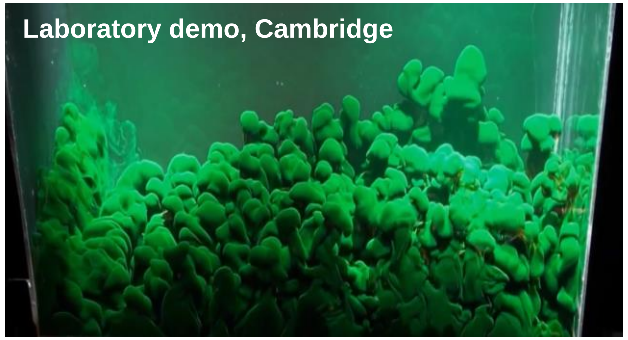
Kelvin-Helmholtz (KH), Rayleigh-Taylor (RT), and Richtmyer-Meshkov (RM)

Kelvin-Helmoltz

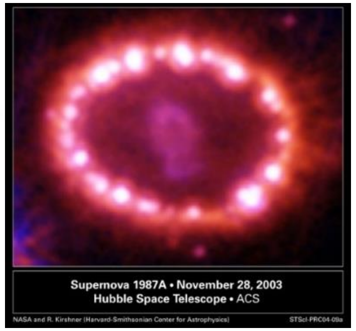


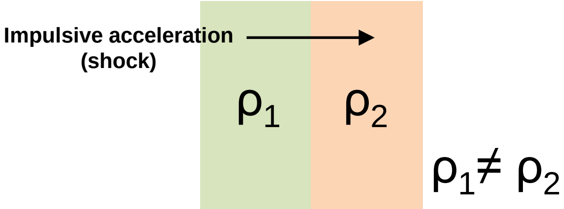
Rayleigh-Taylor

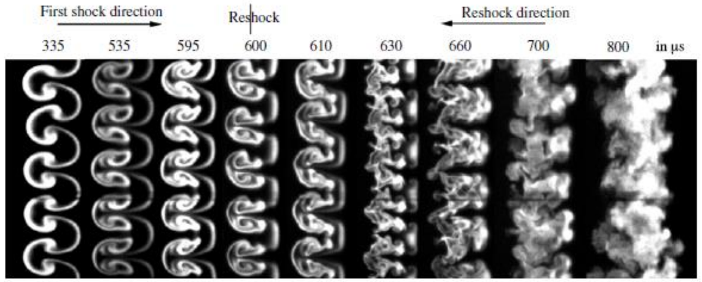




Richtmyer-Meshkov







Tomkins, C. D., *et al.* J. Fluid Mech. (2013) 735

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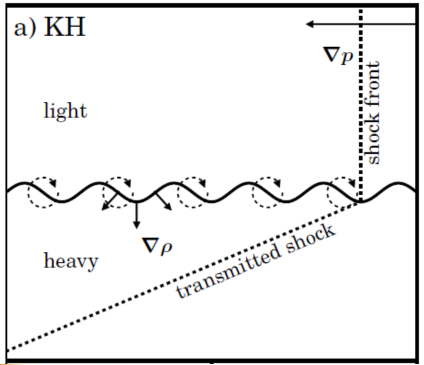
Kelvin-Helmholtz (KH), Rayleigh-Taylor (RT), and Richtmyer-Meshkov (RM)

Kelvin-Helmoltz

v_1 →
v_2 →

v_1 →
← v_2

$v_1 \neq v_2$

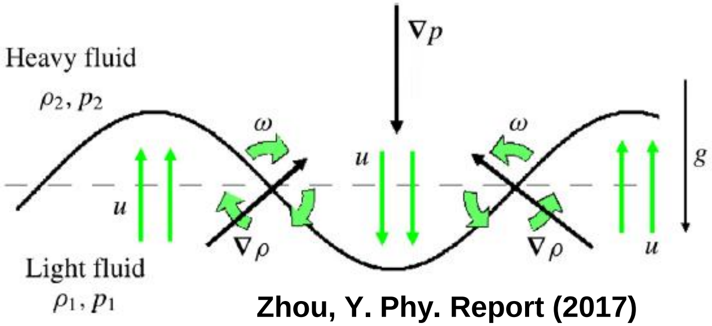


Rasmus, A. M. *et al.*, *PoP*, accepted

Rayleigh-Taylor

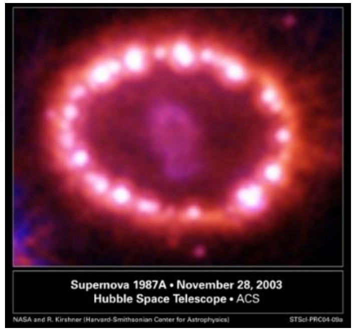
Force ↓

Heavy fluid
Light fluid



Zhou, Y. Phy. Report (2017)

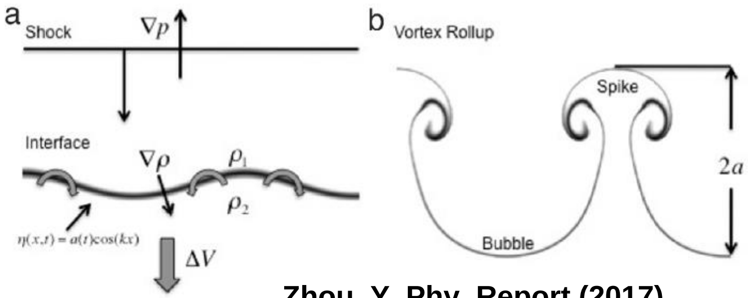
Richtmyer-Meshkov



Impulsive acceleration (shock) →

ρ_1 | ρ_2

$\rho_1 \neq \rho_2$



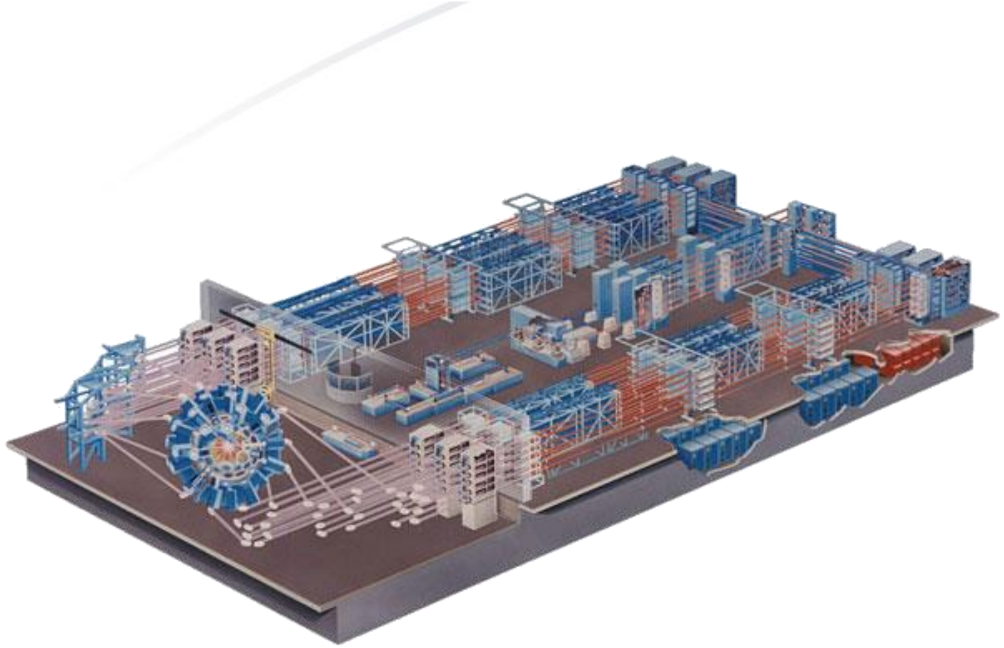
Zhou, Y. Phy. Report (2017)

Each of these instabilities is caused by the deposition of baroclinic vorticity

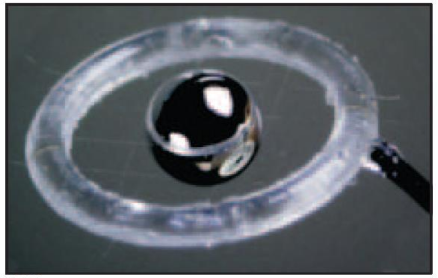
Laser Facilities and Diagnostic Capabilities

LA-UR-15-28742

OMEGA 60 has sixty beams to explore HED and direct-drive ICF implosions



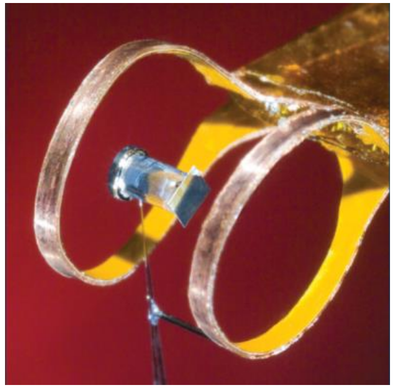
www.lle.rochester.edu/



TC6659

Figure 102.16
A Saturn target shot on OMEGA. Using eight strands of spider silk, a standard 865-μm-diam capsule is mounted on a CH ring of major radius 1100 μm and minor radius 150 μm.

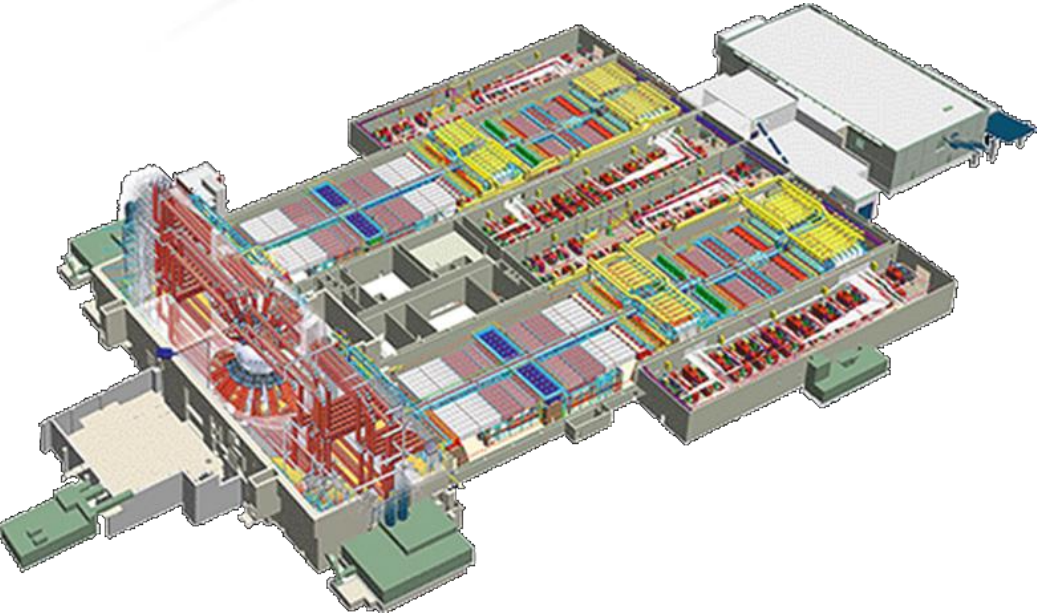
LLE Review 102



LLE Review 110

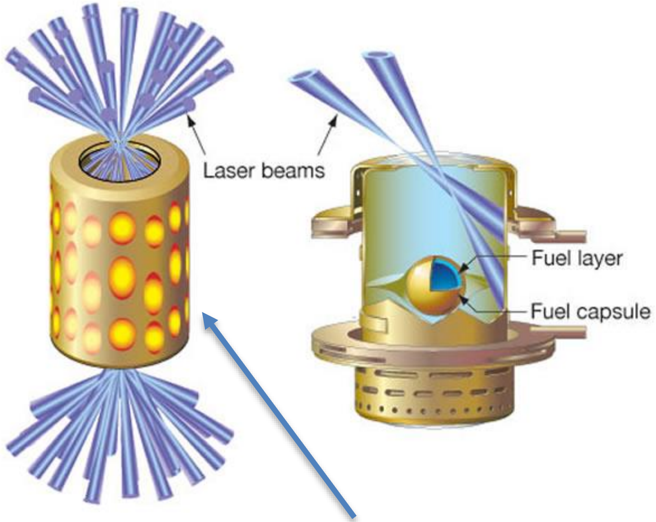
LA-UR-15-28742

The National Ignition Facility uses 192 beams (2MJ) to compress millimeter size targets



https://lasers.llnl.gov/about/what-is-nif

192 Lasers: 500 trillion watts in 20 ns



deuterium (H with 1 neutron)
+ tritium (H with 2 neutrons)

Fuel capsule

LLNL *Sci&Tech Review* (1999)

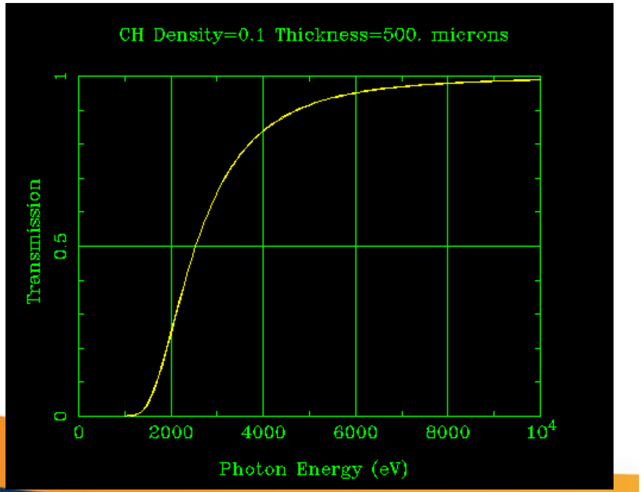
The main diagnostic for HED experiments is X-ray radiography

- Tranmission of materials is well documented:
  http://xdb.lbl.gov/Section1/Sec_1-8.html
- Transmission of x-rays through a slab is described as:

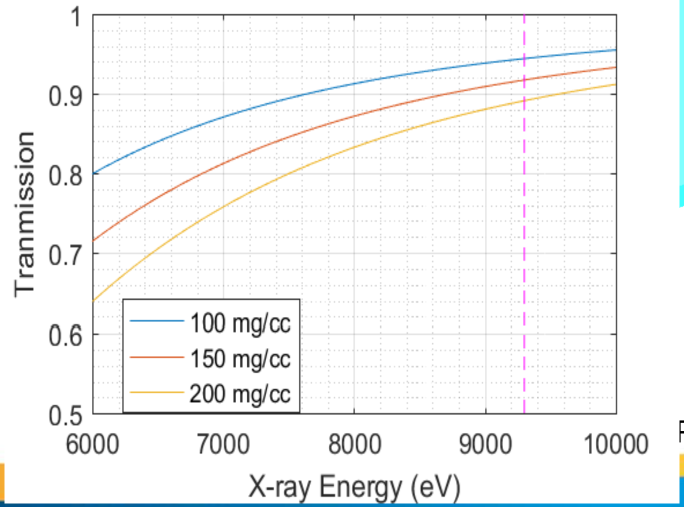
$$T = e^{-n\,\mu_a d}$$

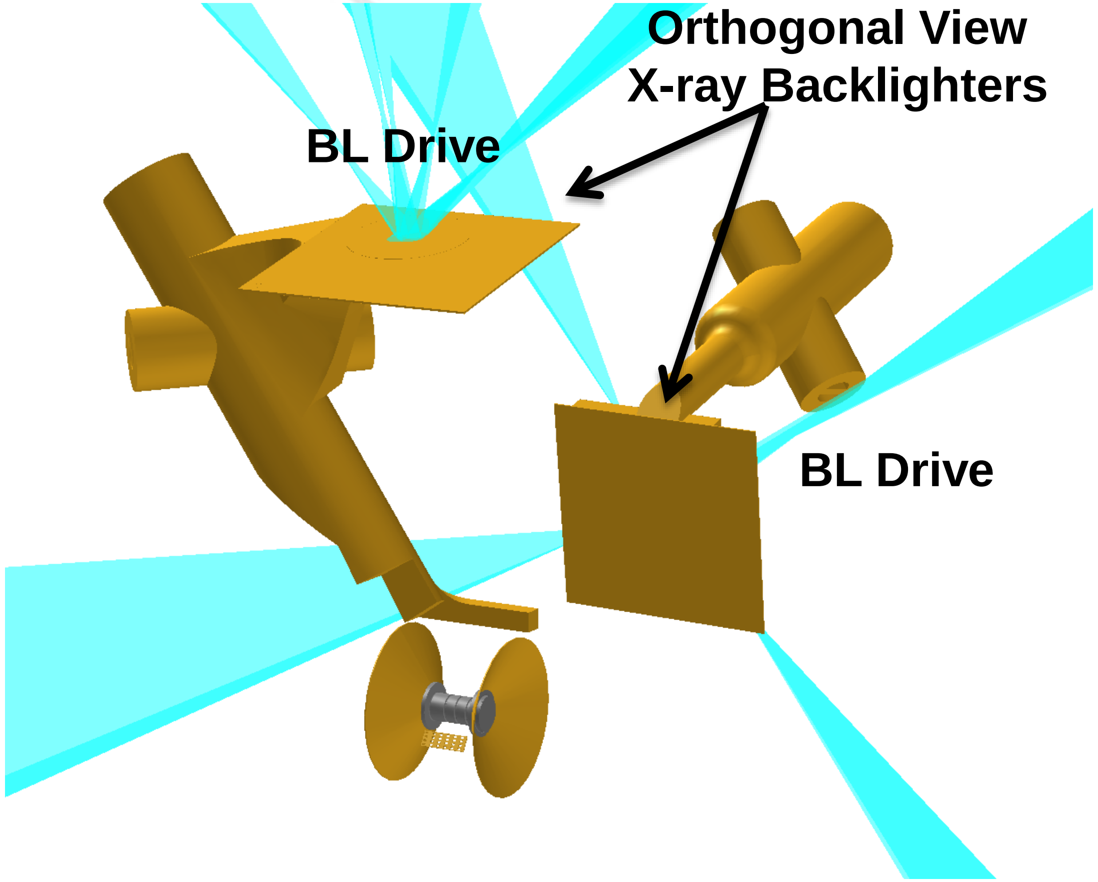
μ_a=photoabsorption cross-section
n=number of atoms per unit volume
d=thickness of slab

- Henke curves provide source of estimating absorption
  http://henke.lbl.gov/optical_constants/



Transmission of CH Foam for changing density



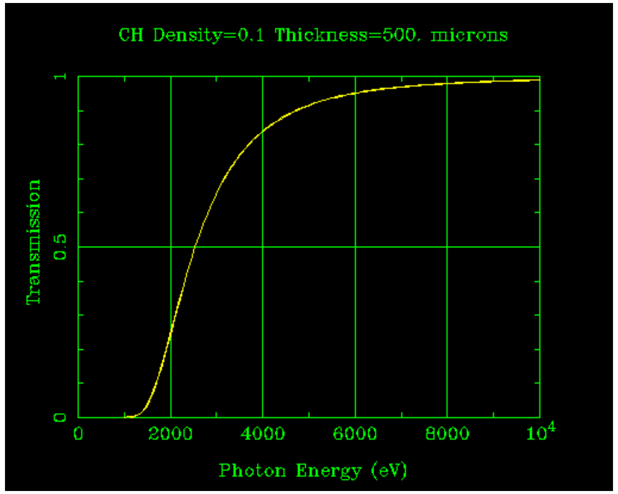


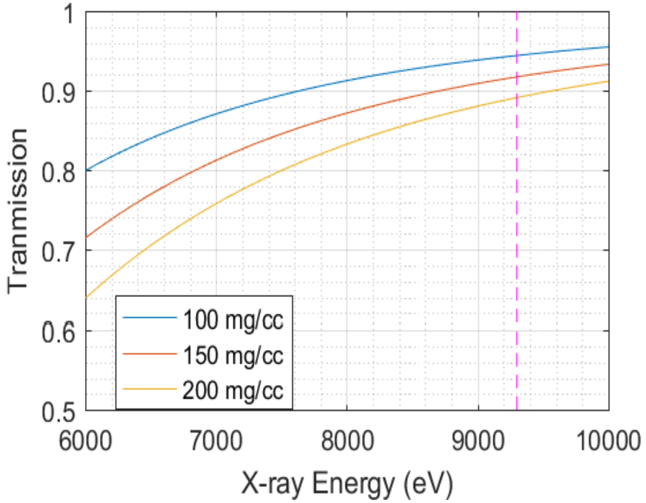
FIED

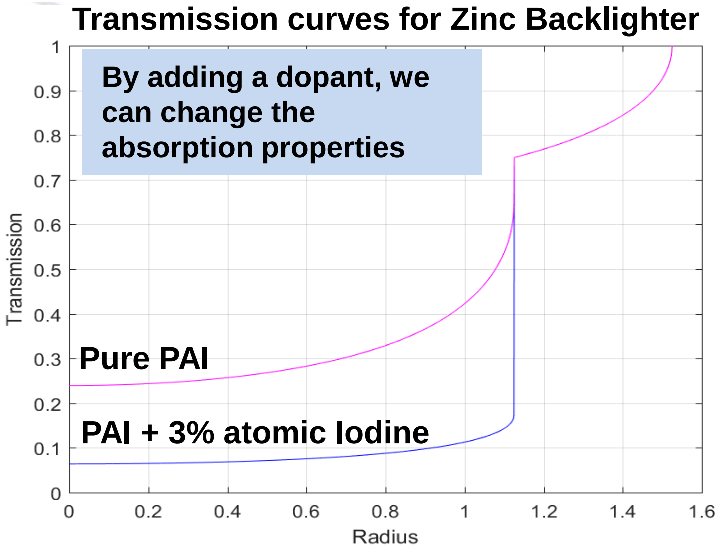
The main diagnostic for HED experiments is X-ray radiography

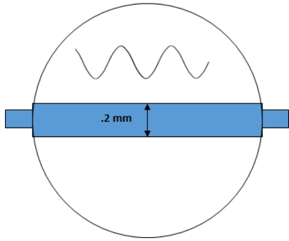
- Every material:
  - generates x-rays in a different regime
  - absorbs x-rays only in certain energy ranges
- Henke curves provide source of estimating absorption

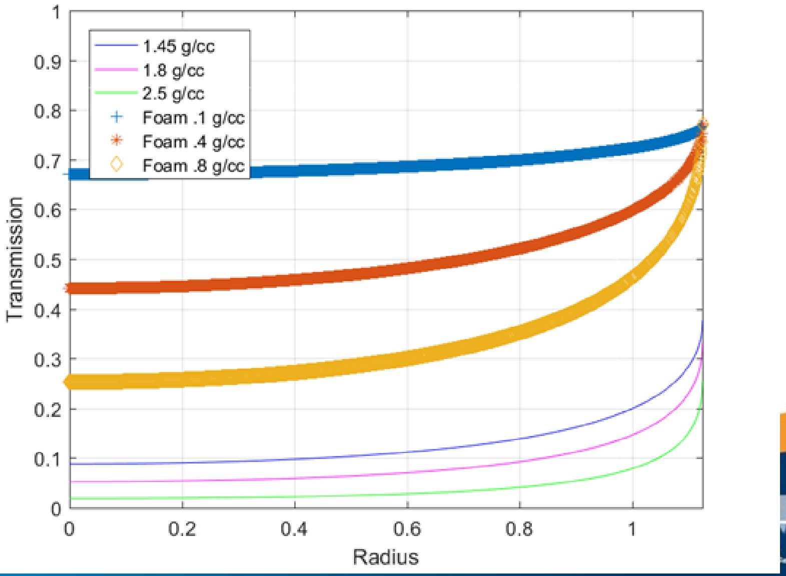
  http://henke.lbl.gov/optical_constants/







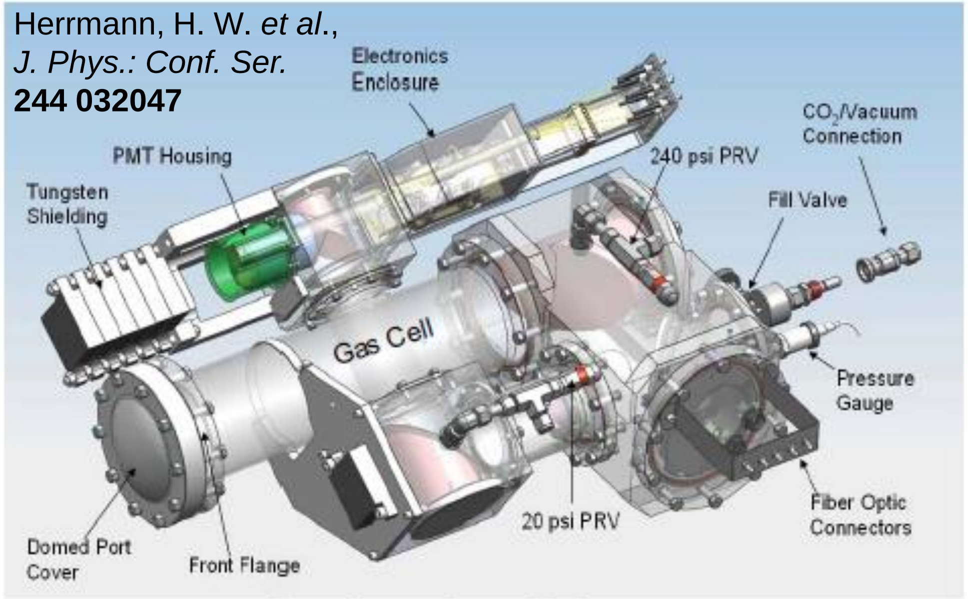




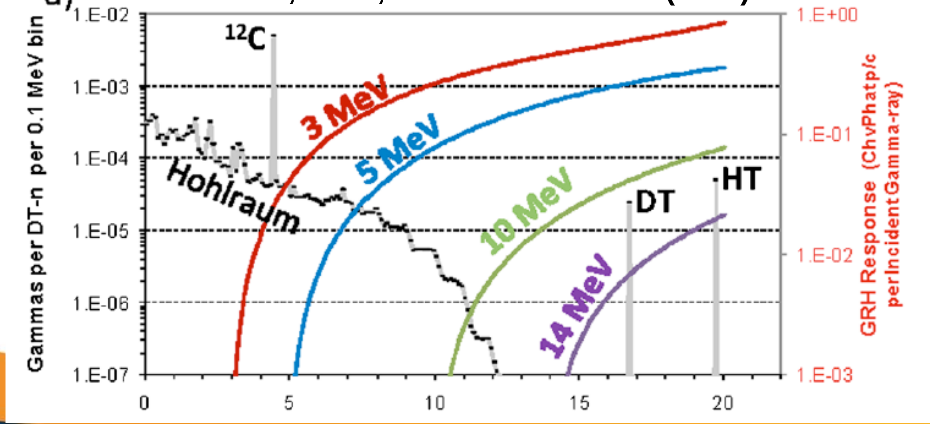
ICF capsules also measure spectra, gamma rays and neutrons

Gamma Ray Detector and sample signal

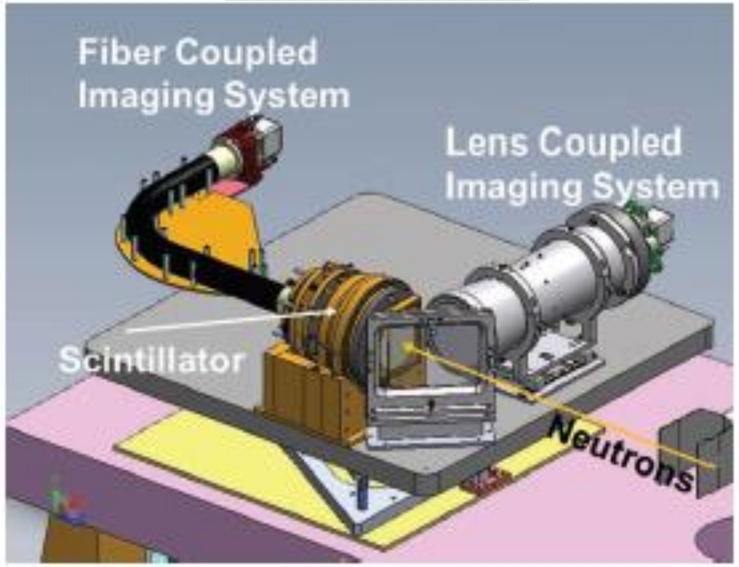
Herrmann, H. W. *et al.*,
J. Phys.: Conf. Ser.
244 032047



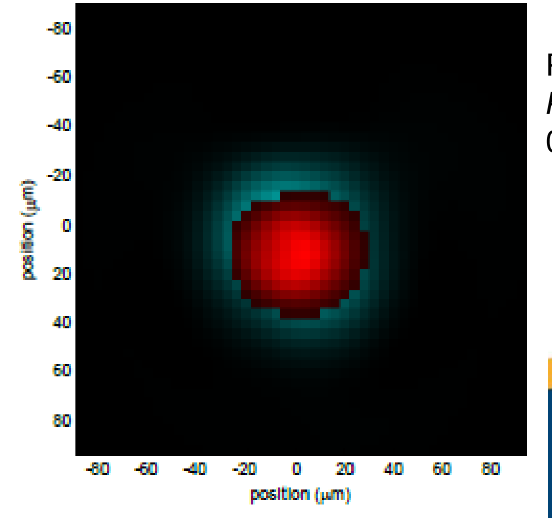
Herrmann, H. W., *et al.* Rev. Sci. Inst. (2010) 81



Neutron Detector



Merrill, F. E., *et al.* Rev. Sci. Inst. (2012) 83



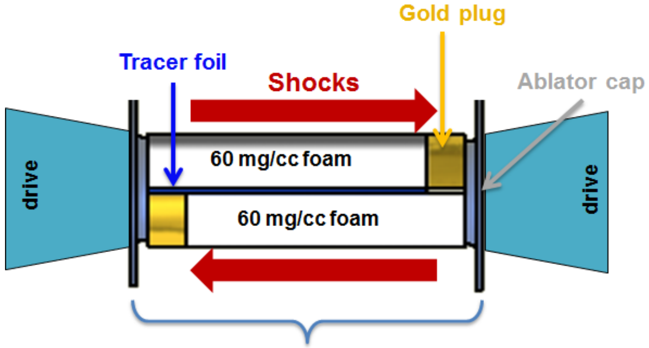
F E Merrill *et al* 2016 *J. Phys.: Conf. Ser.* **688** 012064

Experiments

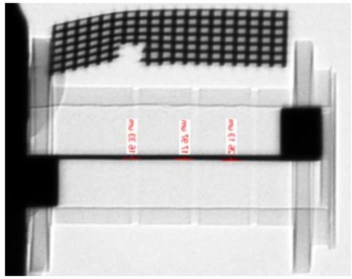
The *Shear* experiment studied counter-propagating shocks to generate the KH instability

OMEGA Experiments

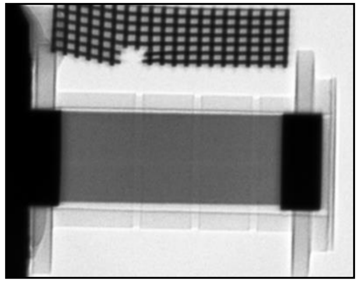
- Drive Energy =8 kJ
- Experiment duration = 16 ns
- 2 Mbar post-shock pressures
- 70 um/ns (km/s) flow speeds
- T = 40 eV



Edge-on View



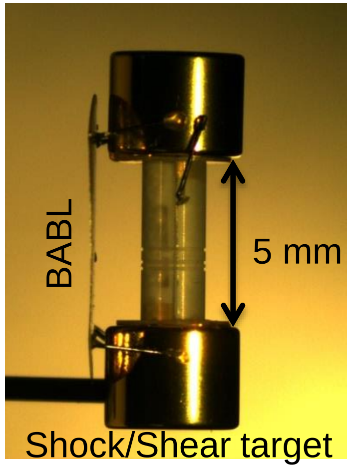
Plan View



NIF Experiments

Same basic design but

- 3x longer, 3x wider
- 600 kJ drive
- Larger volume
  - decreased edge effects
- Longer drive
  - Transients moved later in time
  - Extended experiment duration
    - Closer to turbulent regime



The NIF platform is cleaner and better for turbulence experiments, but the OMEGA platform is better for development

The classical shear layer is characterized by periodic structures in both streamwise and spanwise directions

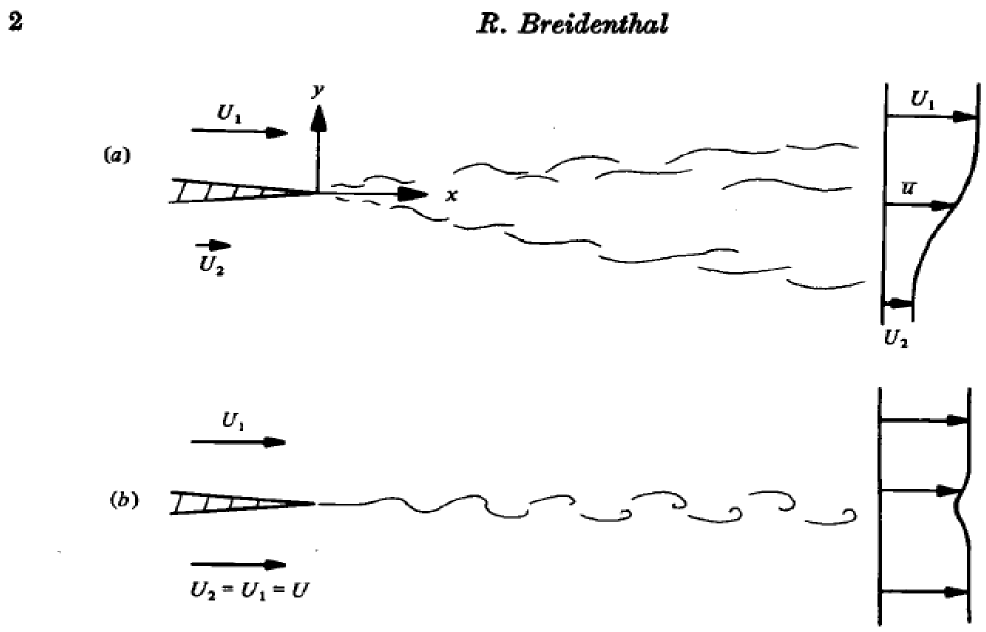
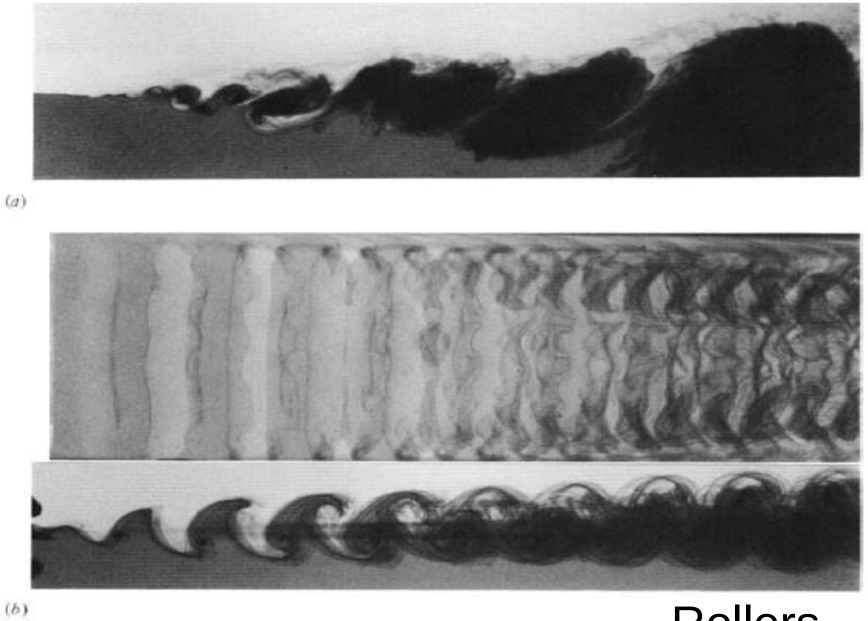


FIGURE 1. (a) Plane mixing layer. (b) Plane wake, thin trailing edge.



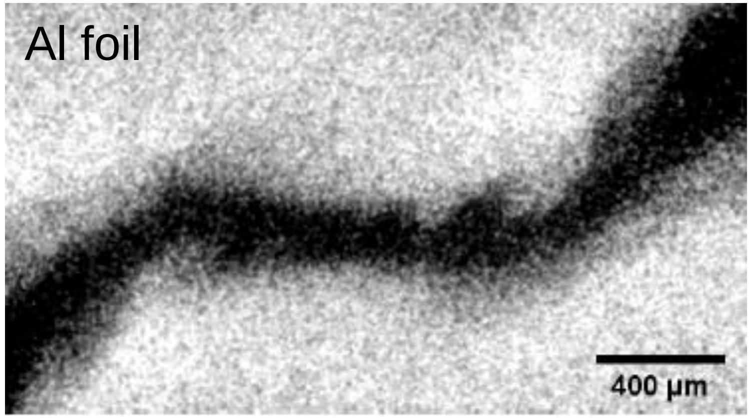
Rollers

R. Breidenthal, “Structure in turbulent mixing layers and wakes using a chemical reaction,” Journal of Fluid Mechanics **109**, 1 (1981).

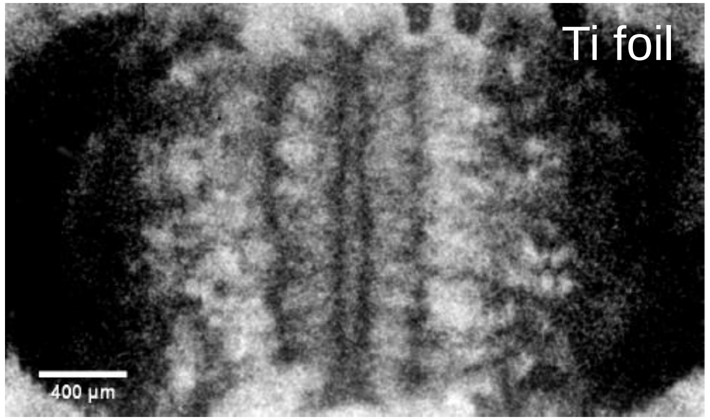
NIF Shear experiments produced the first observations of emergent coherent rollers associated with KH mixing in the HED regime

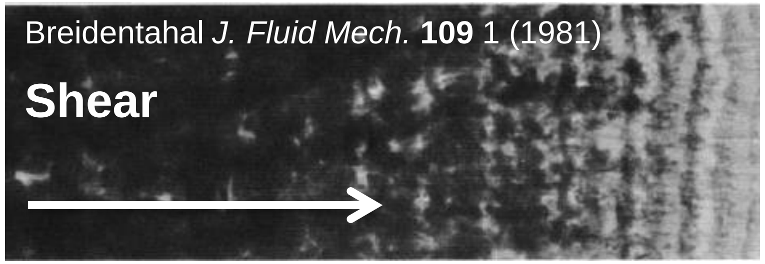
Doss *et al*,. *PRE* **94,** 023101 (2016)

Edge View: N141016, 34.5 ns



Plan View: N150604, 34.5 ns





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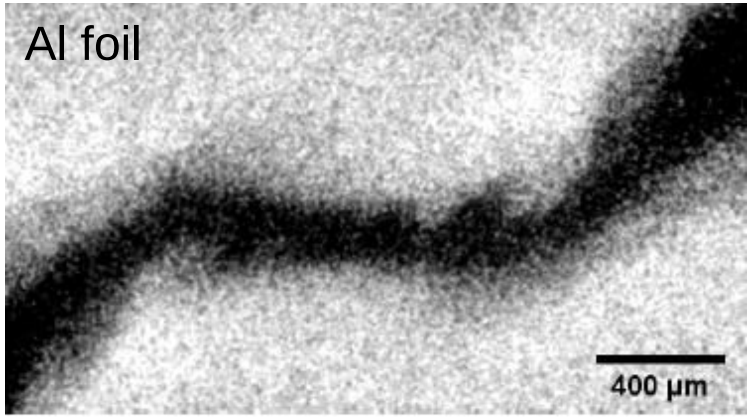
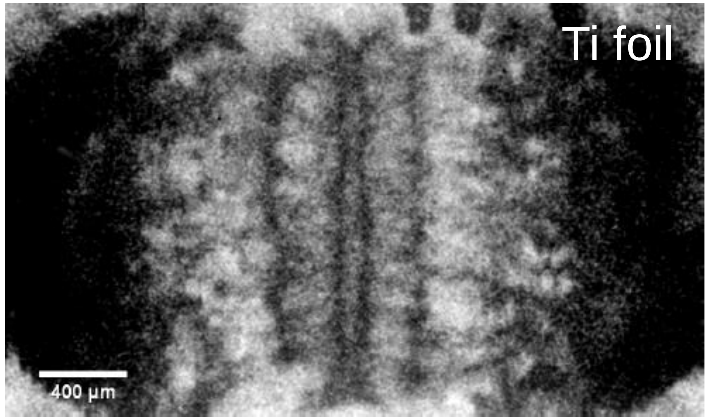
NIF Shear experiments produced the first observations of emergent coherent rollers associated with KH mixing in the HED regime

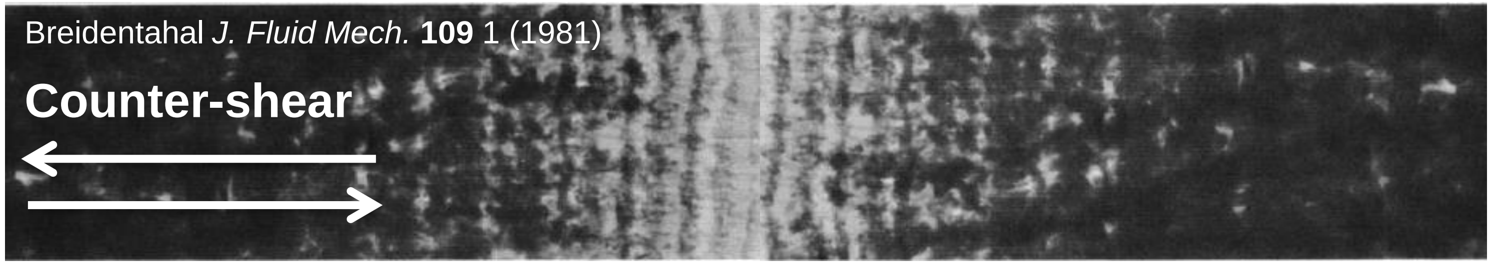
Doss *et al*,. *PRE* **94,** 023101 (2016)

Edge View: N141016, 34.5 ns



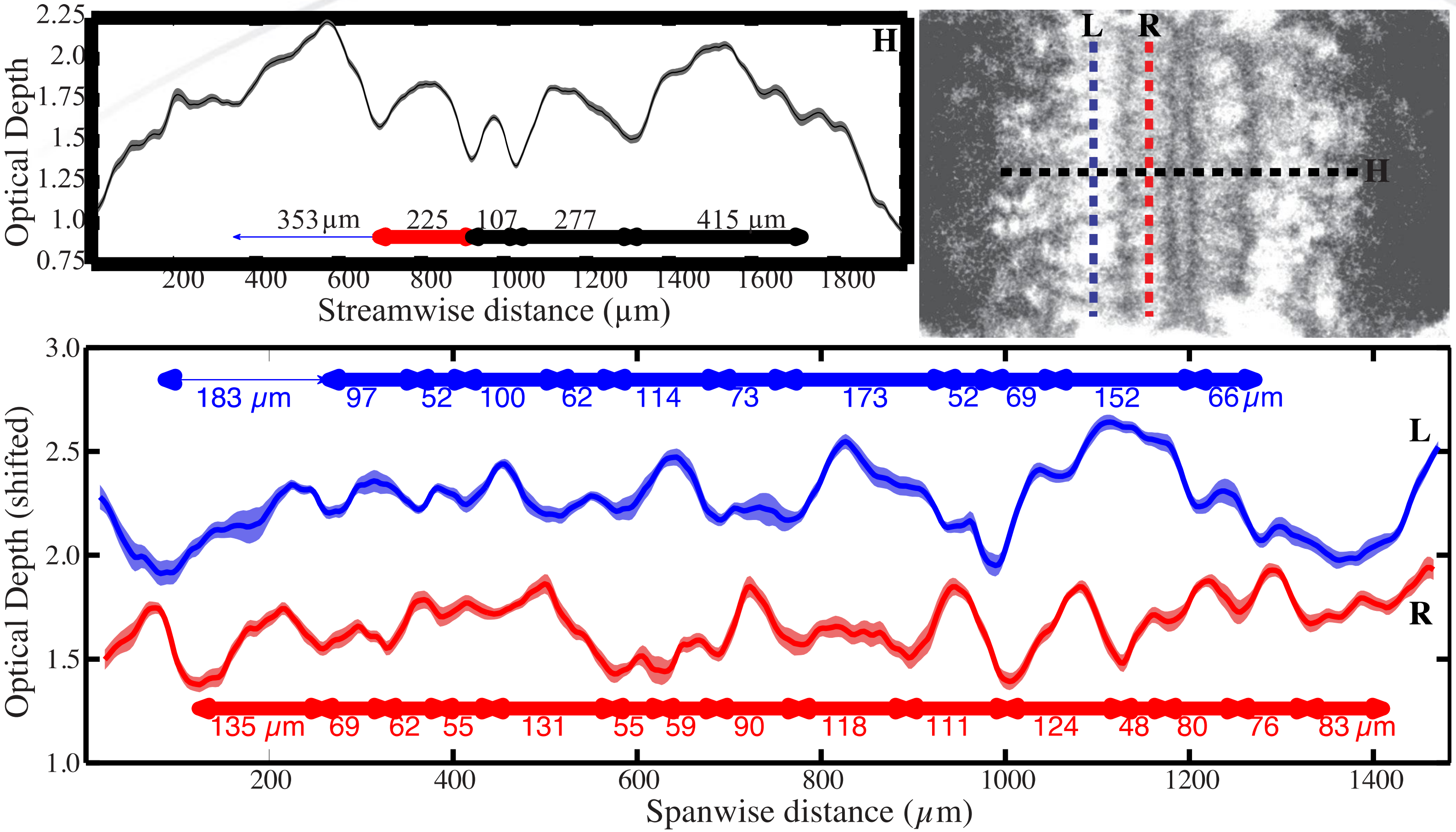
Plan View: N150604, 34.5 ns





Experiments allow us to relate large structure periodicity to the large body of work on planar mixing layer phenomenology and obtain kinetic energy measurements otherwise unobtainable in the HED environment

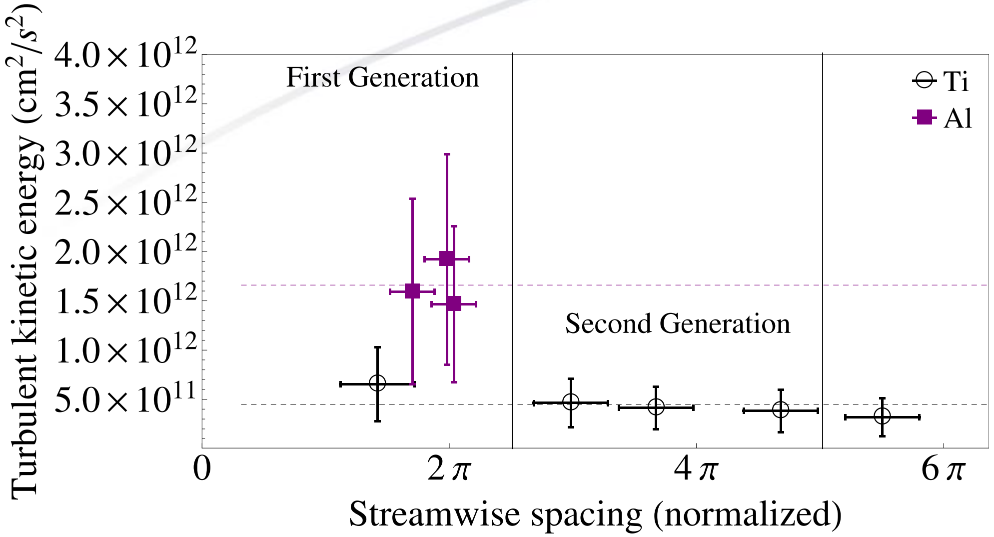
Secondary shear instabilities are measurable and can yield information on the TKE

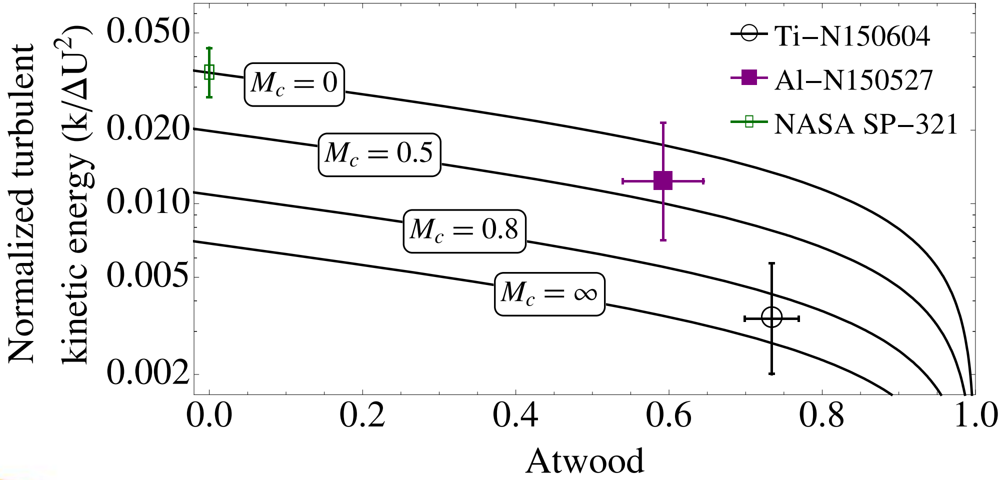


- Lineouts from titanium plan view (N150604) show structure both within and between the KH rollers.
- In ongoing research, higher-order structure in lineouts may inform additional variables.

Phys. Rev. E, **94**, 023101 (2016)

The Merger Rate lets you pull out the Turbulent Kinetic Energy

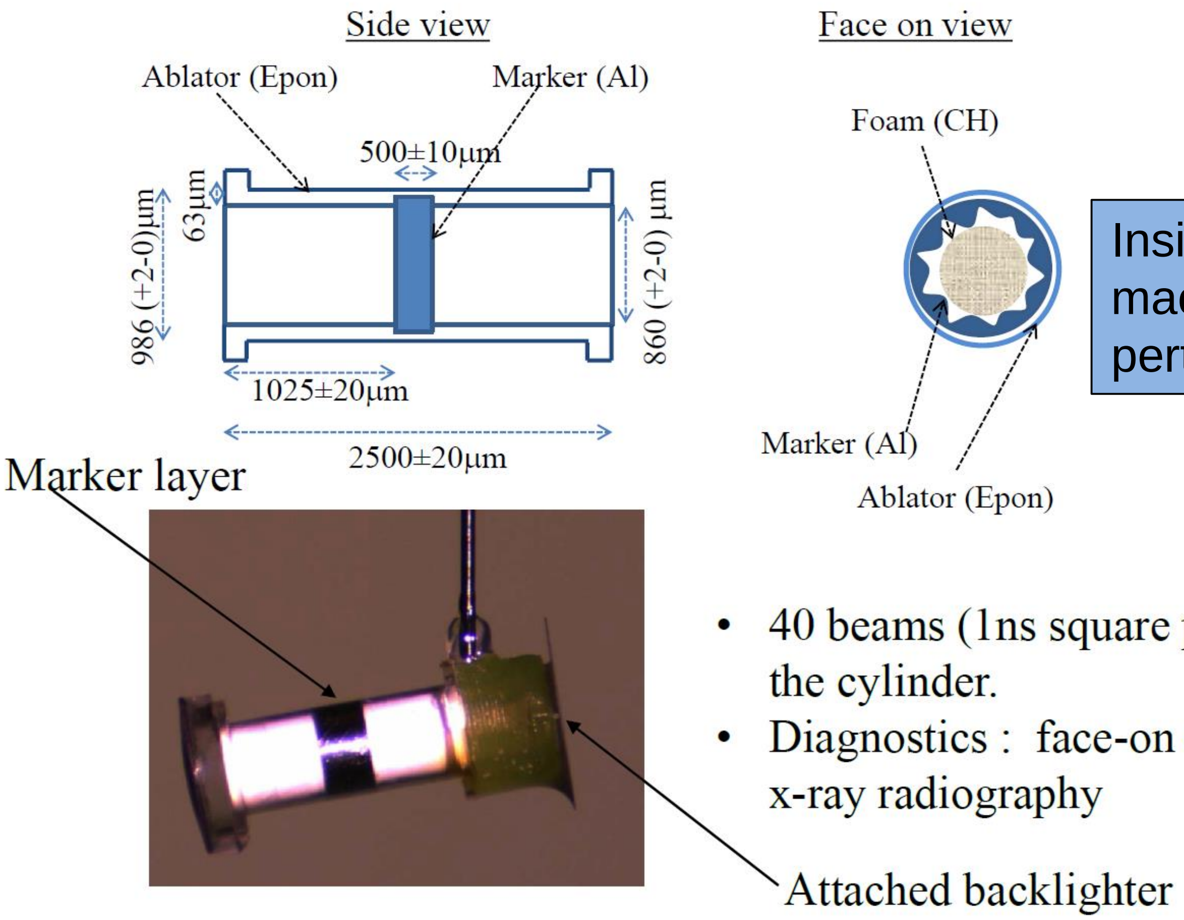




- **Analysis of eight lineouts show consistent energy measurements in each shot.**
- **Inferred energies are broadly consistent with nondimensional scaling for supersonic, high-Atwood mixing layers.**
- **Titanium inferred to have lower energy conversion to mix than lower-density aluminum.**
- **Inferred energies assume all the core rotation (forcing mergers) is from TKE**
- **Other effects could be making this happen, plasma effects, self-generated fields, etc.**

Phys. Rev. E, **94**, 023101 (2016)

CylDRT is studying the deceleration phase of Rayleigh-Taylor instability



Inside surface is machined with perturbations

- 40 beams (1ns square pulse) drive the cylinder.
- Diagnostics : face-on and side-on x-ray radiography

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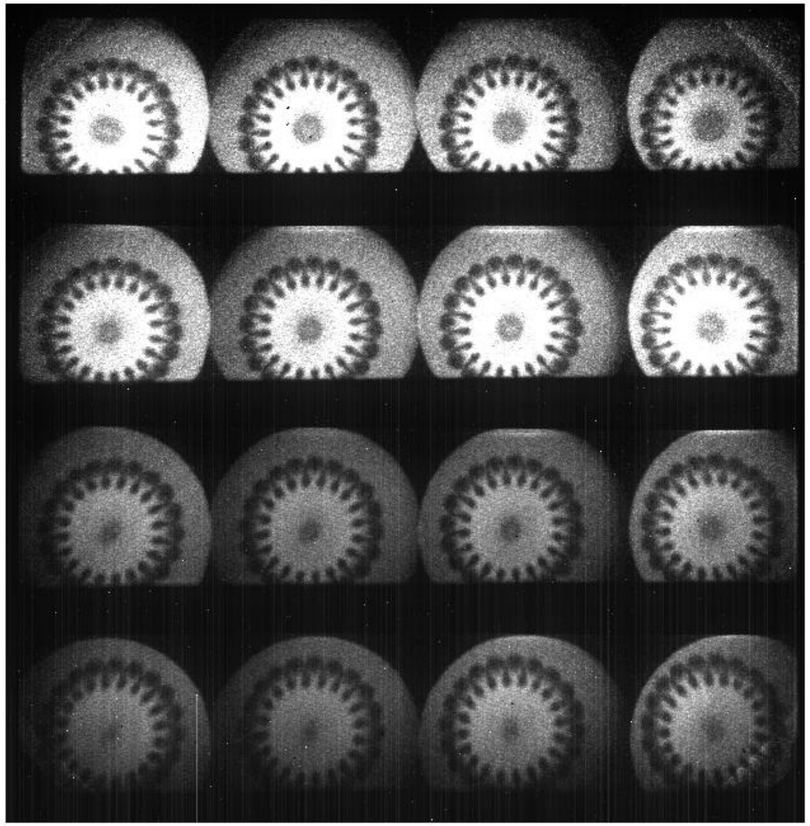
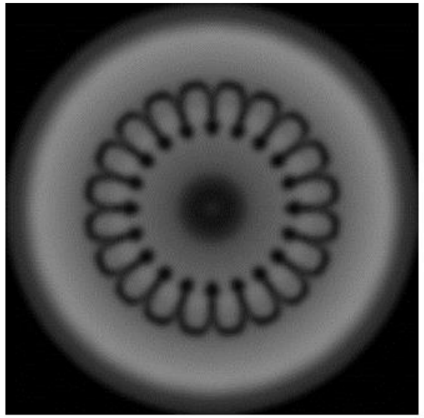
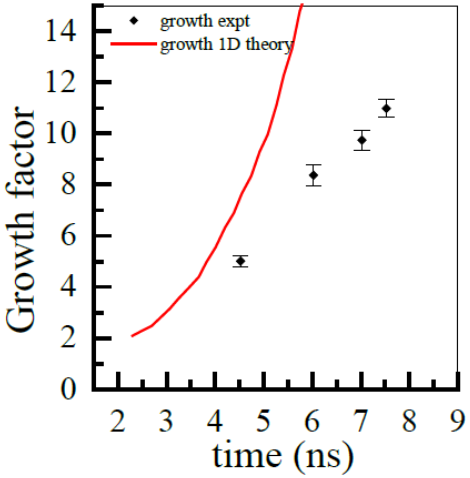
CylDRT is able to capture non-linear growth of late-time RT with single mode perturbations

7.1 ns
6.9 ns
6.7 ns
6.5 ns

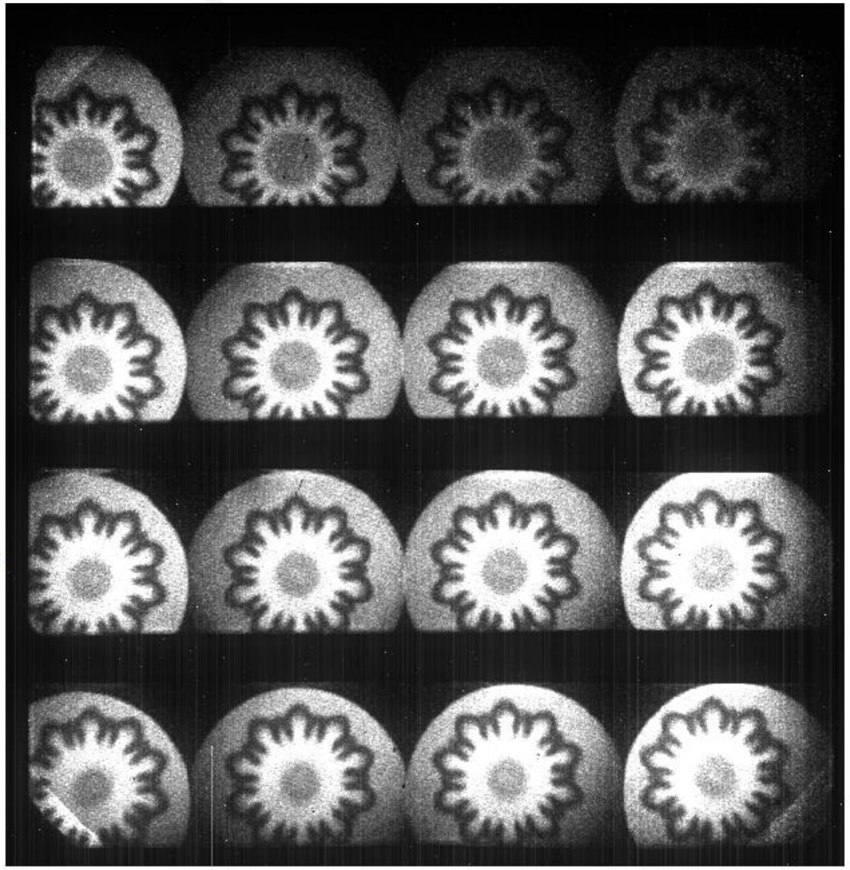




Synthetic Radiograph t=7ns



7.6 ns
7.4 ns
7.2 ns
7.0 ns

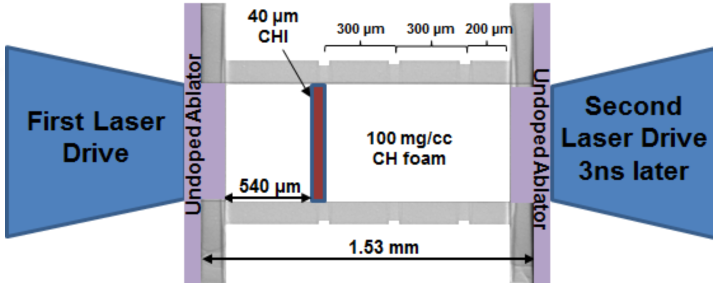


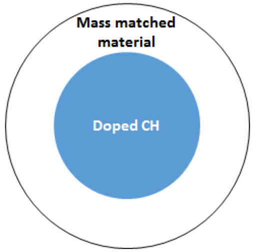
Future experiments will study the multi-mode perturbations

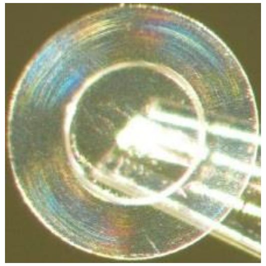
Mshock is studying the feedthrough of the Richtmyer-Meshkov instability in a thin layer

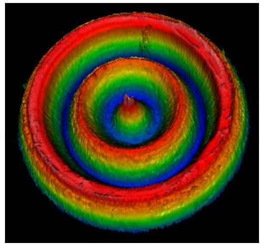
Typical OMEGA Setup

Experiment lasts ~16 ns



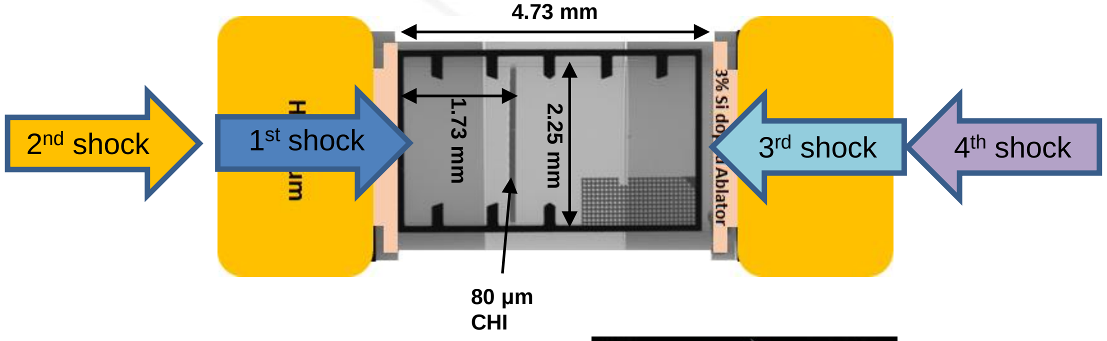


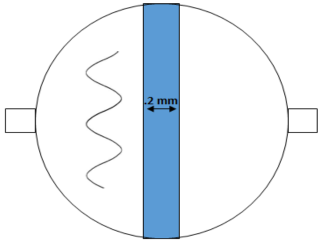


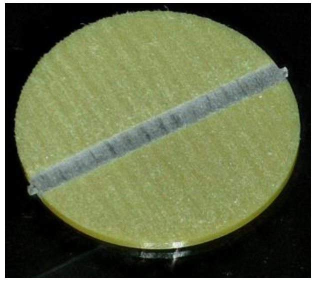


Current NIF Setup

Experiment lasts ~30 ns



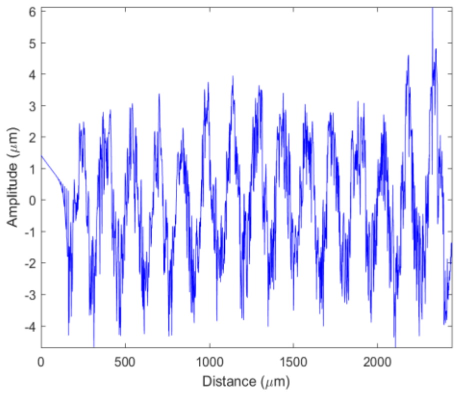


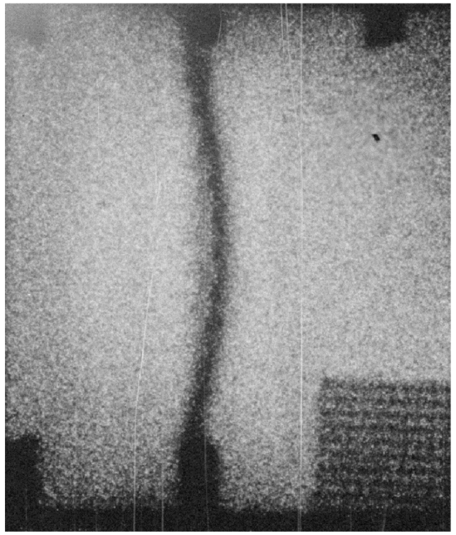


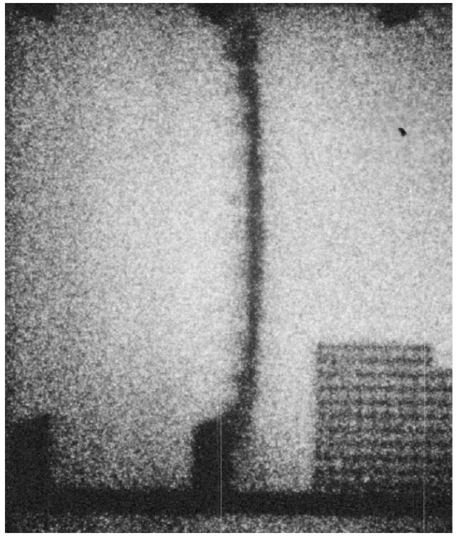
- To improve feature resolution we utilize doping profiles
- Surface are precision machined with surface profiles and perturbations

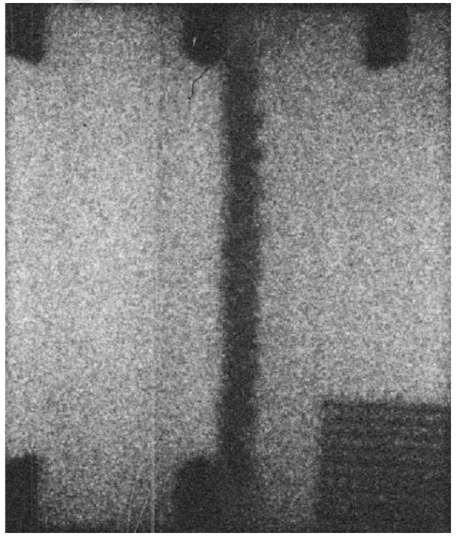
Images of Zygo scan of high density

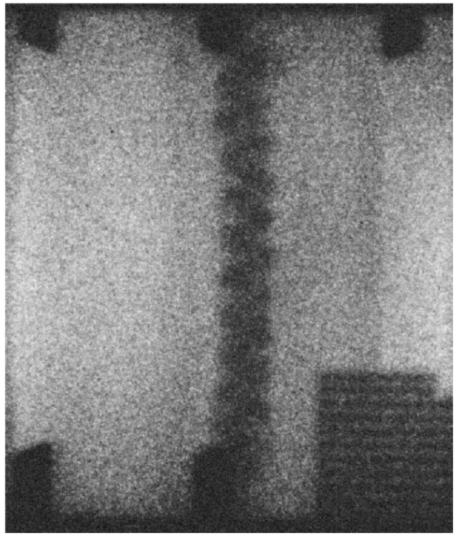
NIF *Mshock* has shown different growth patterns with a change in initial conditions

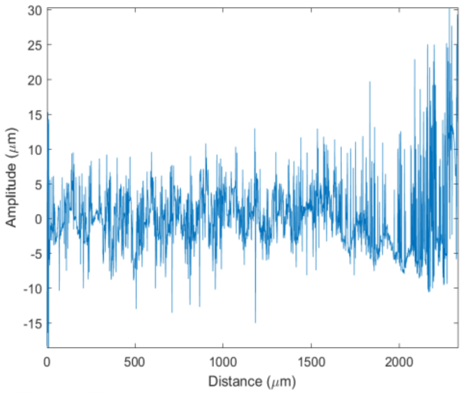


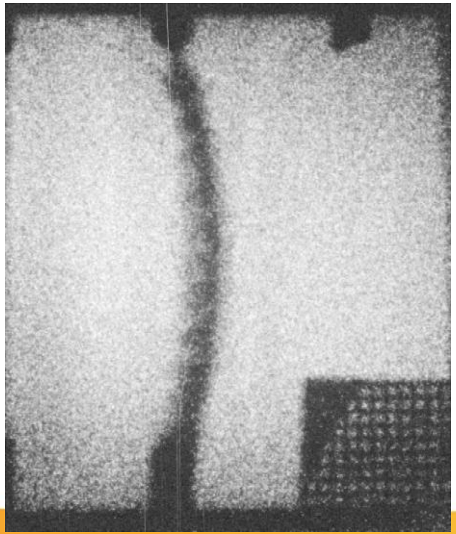


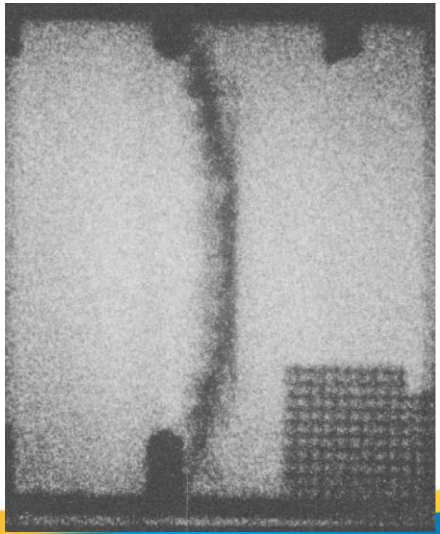




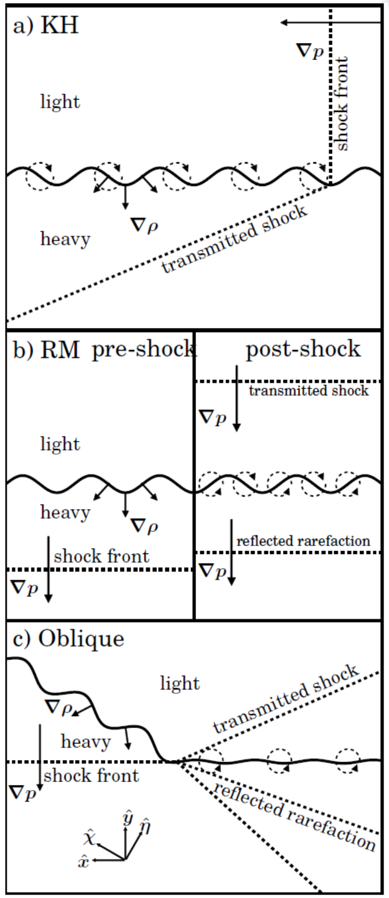


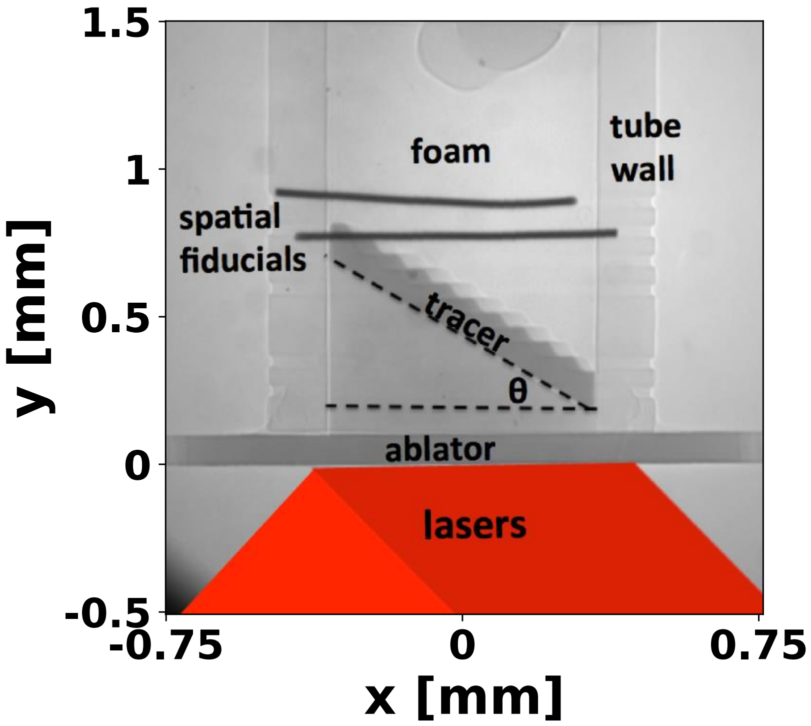






Oblique shock is studying the combination of RM and KH instability

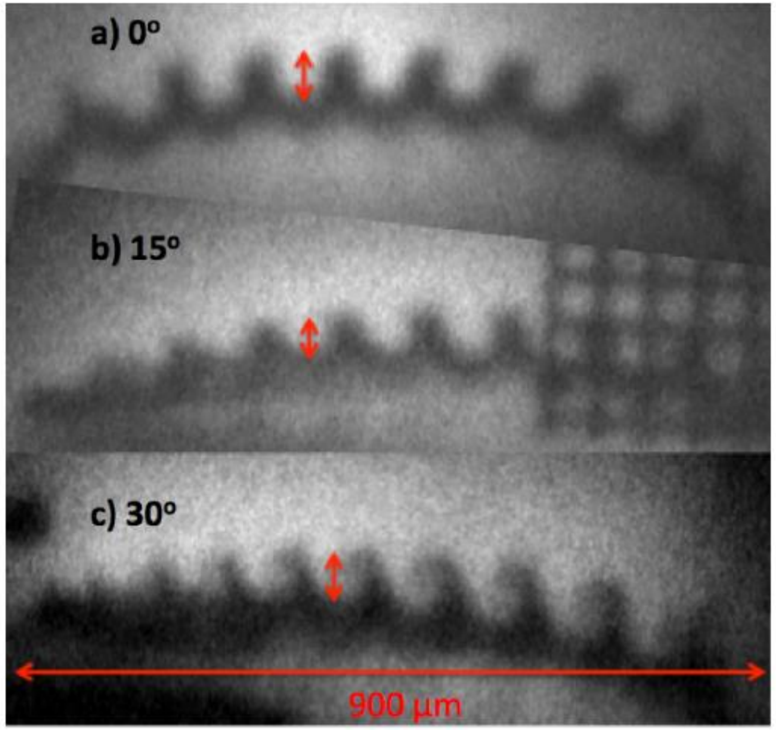




- **Lasers irradiate a PAI layer (1.45 g/cc) at 1.4 x 10^{14} W cm^{-2}**
- **A density matched CHI layer is provides contrast in x-ray radiographs**
- **CH foam (100 mg /cc) is the “light” material**
- **The physics takes place in a CH shock tube with 200 um thick walls.**

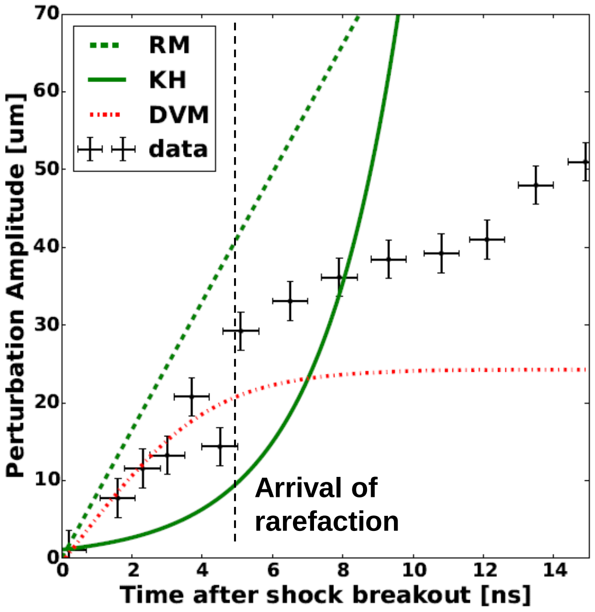
Rasmus, A. M. *et al., PoP*, accepted

Discrete vortex model is able to describe the growth dynamics at early times



$$\frac{dx}{dt} = \frac{\Gamma(\lambda)}{4\lambda} \frac{\sinh(\frac{2\pi y}{\lambda})}{\cos(\frac{\pi x}{\lambda})^2 + \sinh(\frac{\pi y}{\lambda})^2}$$

$$\frac{dy}{dt} = \frac{\Gamma(\lambda)}{4\lambda} \frac{\sin(\frac{2\pi x}{\lambda})}{\cos(\frac{\pi x}{\lambda})^2 + \sinh(\frac{\pi y}{\lambda})^2},$$



Rasmus, A. M. *et al., PoP*, accepted

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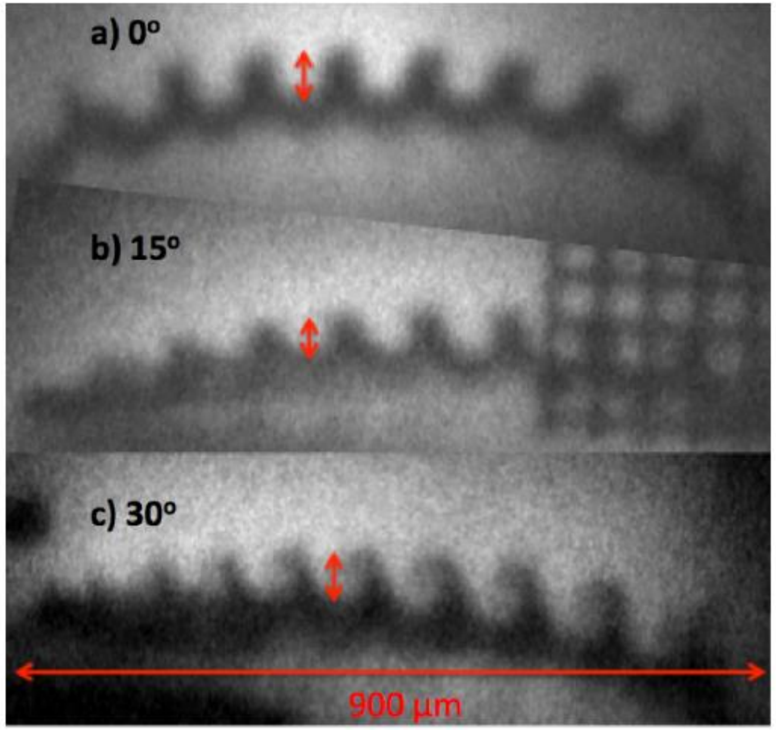
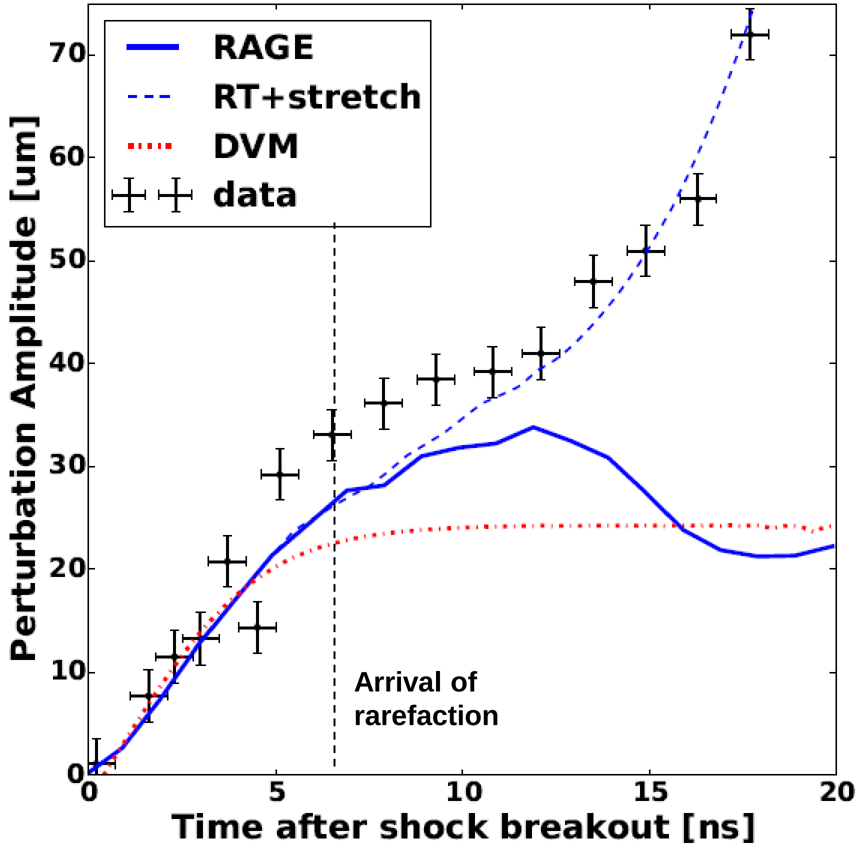
Late time dynamics if dominated by de-acceleration of layer, driving RT instability



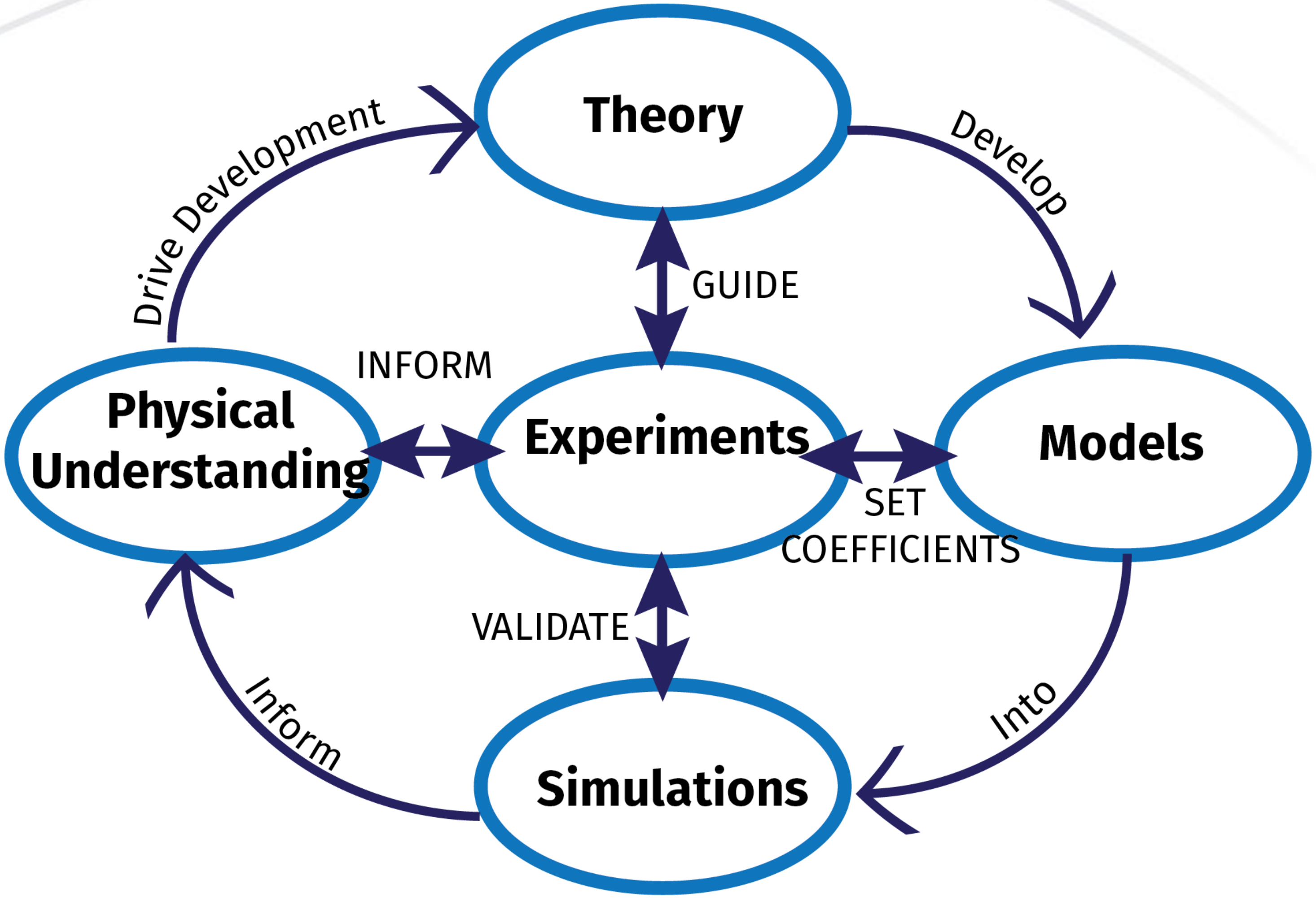


Rasmus, A. M. *et al.*, *PoP*, accepted

UNCLASSIFIED

Simulations

LANL has feedback system for developing fluid codes and mix-models



UNCLASSIFIED

BHR is LANL's mix-model that has been implemented in RAGE (a fluid code)

Los Alamos NATIONAL LABORATORY EST. 1943

Active scalars / Treatment of flow	Flow only (evolves $<u_i' u_j'>$)	Algebraic closure for density effects	Evolution equation for $<u_i' \rho'>$ (k-L-a)	Evolution equation for $<\rho' \rho'>/<\rho' \rho^{-1}'>$ (k-L-a-b)
One evolution equation (k)	Prandtl, 'Berict über Untersuchungen zur ausgbebildeten Turbulenz,' *Z. Angew. Math. Mech* (1925)	Andronov et al., 'Turbulent mixing at a contact surface accelerated by a shock wave,' *Zh. Eksp. Teor. Fiz.* (1976)		
Energy + scale (Two-equation k-ε/L/s/ω)	Harlow & Nakayama, 'Turbulence Transport Equations,' *PoF* (1967) Jones & Launder, 'Prediction of laminarization with a two-equation model of turbulence' *Int. J. H. M. Trans.* (1972)	Gauthier & Bonnet, 'A k–ε model for turbulent mixing in shock tube flows induced by RT,' *PoF* (1990) Dimonte & Tipton 'K-L model for self-similar growth of RT & RM' *PoF* (2006)	Morgan & Wickett 'Three-equation model for the self-similar growth of RT and RM instabilities' *PRE* (2015) Banerjee, Gore, Andrews, *PRE* (2010)	Ruffin et al., 'Characteristic scales in variable-density jets using a second-order model' *PoF* (1993)
Anisotropic effects, Reynolds stress tensor (R_{ij}–ε) Transient effects, two-scales (R_{ij}–ε_1–ε_2)	Rotta, 'Statistische Theorie nichthomogener Turbulenz,' *Z. Phys.* (1951) LRR, 'Development of a Reynolds-stress turbulence closure,' *JFM* (1975)			Schwarzkopf et al. *JoT* (2011), *Flow Turb. Comb* (2016) Grégoire, Souffland, Gauthier, 'A second-order turbulence model for gaseous mixtures' *JoT* (2005)

NNSA National Nuclear Security Administration

Brief history of the BHR mix model

Treatment of flow / Active scalars	Flow only (evolves $\langle u_i' u_j' \rangle$)	Algebraic closure for density effects	Evolution equation for $\langle u_i' \rho' \rangle$ (k-L-a)	Evolution equation for $\langle \rho' \rho' \rangle / \langle \rho' \rho^{-1\prime} \rangle$ (k-L-a-b)
One evolution equation (k)	Prandtl, 'Bericht über Untersuchungen zur ausgbebildeten Turbulenz,' *Z. Angew. Math. Mech* (1925)	Andronov et al., 'Turbulent mixing at a contact surface accelerated by a shock wave,' *Zh. Eksp. Teor. Fiz.* (1976)		
Energy + scale (Two-equation k-ε/L/s/ω)	Harlow & Nakayama, 'Turbulence Transport Equations,' *PoF* (1967) Jones & Launder, 'Prediction of laminarization with a two-equation model of turbulence' *Int. J. H. M. Trans.* (1972)	Gauthier & Bonnet, 'A k–ε model for turbulent mixing in shock tube flows induced by RT,' *PoF* (1990) Dimonte & Tipton 'K-L model for self-similar growth of RT & RM' *PoF* (2006)	Morgan & Wickett 'Three-equation model for the self-similar growth of RT and RM instabilities' PRE (2015) Banerjee, Gore, Andrews, *PRE* (2010)	Ruffin et al., 'Characteristic scales in variable-density jets using a second-order model' *PoF* (1993)
Anisotropic effects, Reynolds stress tensor (R_{ij}–ε) Transient effects, two-scales (R_{ij}–ε_1–ε_2)	Rotta, 'Statistische Theorie nichthomogener Turbulenz,' *Z. Phys.* (1951) LRR, 'Development of a Reynolds-stress turbulence closure,' *JFM* (1975)			Schwarzkopf et al. *JoT* (2011), *Flow Turb. Comb* (2016) Grégo... ...land, Gauthier, 'A second-or... ...odel for gaseous mixtures' *JoT* (2...

"BHR-1"

"BHR-2"

"BHR-3"

Besnard, Harlow, Rauenzahn
"Conservation and transport properties of turbulence with large density variations"
LA-10911-MS

BHR (theory)
1982

BHR[3.1] with full Reynold Stress Tensors

Turbulent kinetic energy

$$\begin{aligned}\frac{\partial\left(\bar\rho \tilde R_{ij}\right)}{\partial t} + \left(\bar\rho \tilde u_k \tilde R_{ij}\right)_{,k} = {} & \overbrace{\left[a_i \bar P_{,j} + a_j \bar P_{,i}\right] - \bar\rho\left[\tilde R_{ik}\tilde u_{j,k} + \tilde R_{jk}\tilde u_{i,k}\right]}^{\text{Production}} \\ & + \underbrace{C_r\left(\frac{L}{\sqrt K}\bar\rho \tilde R_{kn}\tilde R_{ij,n}\right)_{,k}}_{\text{Diffusion}} \underbrace{- C_{r3}\bar\rho\frac{\sqrt K}{L}\left(\tilde R_{ij} - \frac{1}{3} \tilde R_{kk}\delta_{ij}\right)}_{\text{Return to isotropy}} \\ & \overbrace{- C_{r1}\left[a_i\bar P_{,j}+a_j\bar P_{,i}\right] + C_{r2}\bar\rho\left[\tilde R_{ik}\tilde u_{j,k}+\tilde R_{jk}\tilde u_{i,k}\right]}^{\text{Rapid Distortion}} \\ & \underbrace{- C_{r2}\frac{2}{3}\bar\rho\tilde R_{mk}\tilde u_{m,k}\delta_{ij} + C_{r1}\frac{2}{3} a_k\bar P_{,k}\delta_{ij}}_{\text{Rapid Distortion}} \underbrace{-\bar\rho\frac{2}{3}\frac{K^{3/2}}{L}\delta_{ij}}_{\text{Dissipation}}\end{aligned}$$

Turbulence scale

$$\frac{\partial\left(\bar\rho L\right)}{\partial t} + \left(\bar\rho\tilde u_j L\right)_{,j} = \underbrace{-\frac{L}{K}\left(\frac{3}{2} - C_1\right)\bar\rho\tilde R_{ij}\tilde u_{i,j} + \frac{L}{K}\left(\frac{3}{2} - C_3\right)a_j\bar P_{,j} - \left(\frac{3}{2} - C_2\right)\bar\rho\sqrt K}_{\text{Net Production}} + \underbrace{C_s\left(\frac{L}{\sqrt K}\bar\rho\tilde R_{kn}L_{,n}\right)_{,k}}_{\text{Diffusion}}$$

Mass flux

$$\frac{\partial\left(\bar\rho a_i\right)}{\partial t} + \left(\bar\rho\tilde u_k a_i\right)_{,k} = \underbrace{b\bar P_{,i} - \tilde R_{ik}\bar\rho_{,k} - \bar\rho a_k\tilde u_{i,k}}_{\text{Net Production}} + \underbrace{\bar\rho\left(a_k a_i\right)_{,k}}_{\text{Redistribution}} + \underbrace{\bar\rho C_a\left(\frac{L}{\sqrt K}\tilde R_{kn}a_{i,n}\right)_{,k}}_{\text{Diffusion}} \underbrace{- C_{a1}\bar\rho\frac{\sqrt K}{L}a_i}_{\text{Destruction}}$$

Mixedness

$$\frac{\partial\left(\bar\rho b\right)}{\partial t} + \left(\bar\rho b\tilde u_k\right)_{,k} = \underbrace{-2\left(b+1\right)a_k\bar\rho_{,k}}_{\text{Production}} + \underbrace{2\bar\rho a_k b_{,k}}_{\text{Redistribution}} + \underbrace{\bar\rho^2 C_b\left(\frac{L}{\bar\rho\sqrt K}\tilde R_{mn}b_{,n}\right)_{,m}}_{\text{Diffusion}} \underbrace{- C_{b1}\bar\rho\frac{\sqrt K}{L}b,}_{\text{Destruction}} \qquad (12.11)$$

UNCORRECTED

Ye Zhou, Rev. Mod Phys.

Schwarzkopf et al. *JoT* (2011), *Flow Turb. Comb* (2016)

- There are three main control knobs for growth in BHR-3
  - s_0 = initial turbulent scale length
  - k_0 = initial turbulent kinetic energy
  - Turn on time of BHR

The next step is called the modal model and will decide when to initialize turbulence

Summary: LANL has a variety of experiments investigating traditional fluids instabilities in an HED regime

- HED experiments are critical for understanding the physics of astrophysical phenomena, as well as ICF
- HED experiments are also important for code development and eventual validation
- There are more experiments upcoming that are investigating potentially missing physics such as magnetic fields

These experiments are just a few of those active in the P-24 group at LANL